LUBRICATING OIL TESTS

AND THEIR SIGNIFICANCE

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PREFACE

THERE is a voluminous literature on lubrication and lubricants, but the majority of these publications are of a highly specialised character appealing particularly to the professional chemist or engineer. It seems that a useful purpose would be served by a short publication dealing with the subject in a more general way, giving a brief review of the essential details of oil technology and it is hoped that these Notes will be helpful to the engineer, the oil user, and the oil salesman.

The jargon of the chemist and engineer has been avoided as far as possible, and the descriptions given in simple language; no attempt has been made to deal with the subject in an exhaustive manner, but it has been the aim throughout to discuss oils and tests especially from the point of view of their application to lubrication.

A further object of these notes is to describe the special features of " GERM " oils in a strictly scientific manner.

The importance of efficient lubrication of engines, automobiles and machines is fully recognised by all engineers and machinery users, but it is not always realised what an immense amount of technical and scientific research has been devoted to the study of lubrication and the production of modern lubricating oils. No small part in the progress of engineering design has been played by the petroleum technologist, and it is no exaggeration to say that the efficiency and reliability of the modern internal combustion motor is due largely to the improvements made in lubrication and lubricating oil in recent years.

In the very earliest times the only lubricating material was derived from the fat of animals and from the seeds and fruit of plants (animal and vegetable oils), and it is said that the axles of the Roman chariots were greased by the fat of the wild boar, supposedly superior to others—the dawn of fancy in lubrication.

The choice of lubricants was restricted to this class of material until the middle of the nineteenth century, when a new source was tapped by the discovery of petroleum mineral oil from which, by ever-improving methods of refining, a continually expanding range of lubricating oil of every conceivable type has been produced.

These mineral oils far surpass the old animal and vegetable oils in their resistance to oxidation and gumming and have rendered possible such engineering triumphs as the Steam Turbine, and the Automobile.

At the same time experience has shown that the highly refined mineral oils are somewhat deficient in lubricating properties, especially under conditions of heavy loading, where the rupture of the oil film is likely to occur, and curiously enough, the more perfectly they are refined the more inefficient they become as reducers of friction. For example the purest mineral oil, " Toilet Paraffin," is a sadly deficient lubricant.

This led to the production of so-called " compounded " oils in which some animal and vegetable oil was blended with the mineral oil, and these products certainly possess the property of resisting rupture of the film under heavy load better than pure mineral oil—but there are drawbacks.

Compounded oils containing a high percentage of an animal or vegetable oil are not sufficiently resistant to oxidation and saponification, and invariably gum and thicken when used in circulation for long periods of time. In searching for a lubricant which would resist high bearing pressures and temperatures while maintaining the chemical stability and freedom from gumming of pure mineral oils, the Author in collaboration with H. M. Wells discovered that the lubricating efficiency of mineral oils could be substantially improved by blending with them a minute amount of certain fatty acids. This discovery was patented in all important countries and the oils so manufactured by this process are known commercially as " GERM " oils.

In the following pages an account of these will be given, and the general methods of testing oil described with particular attention to the practical significance of each test and its relationship to the lubrication of engines and machinery.

In concluding this foreword it should be mentioned that the Wells-Southcombe process has been tested and reported on by the leading scientific authorities in England, Europe, and the U.S.A., where the consumption runs into millions of gallons for the lubrication of automobiles, Diesel engines, gas engines, and general machinery.

The peculiar value of Wells-Southcombe process Oils in lubrication has been confirmed not only in practice, but also in theory, and the principle is now accepted by all scientific authorities.

THE MANUFACTURE OF LUBRICATING OILS

CRUDE petroleum is a complex mixture of organic compounds called Hydrocarbons because they are built up entirely from the two elements carbon and hydrogen. In appearance and composition the crude varies widely, according to its source, from a thin volatile liquid to a thick black, tarry and even semi-solid mass; the first refining operation consists of a distillation process whereby the more volatile gasolene and kerosene is separated from the heavier fractions from which lubricating oil is ultimately obtained.

This distillation used to be carried out in stills which treated a batch of about 600 barrels and worked intermittently, but nowadays the " Pipe " still has largely superseded this method.

In this type of plant the crude is continuously fed through pipes heated in a furnace and the distillates simultaneously collected at various points in the system according to the temperature at which they boil.

Each fraction is washed with suitable chemicals to purify it, subsequently chilled to remove wax, and finally redistilled or filtered.

The most recent development is to distil under high vacuum and collect a fraction containing not only the machinery oil but a portion of the very high boiling material, then remove the impurities by agitation with absorbent earths from which the oil is finally filtered under pressure.

This yields a viscous highly purified product known as Long Residuum. This product is usually chilled to precipitate wax which is then removed by high speed centrifuges yielding an oil of low cold test.

Certain crudes yield a still residue which is worked up into Black Cylinder Stock, and this again on further treatment, and filtration, gives us the Pale Filtered Cylinder Oils.

These various " raw " lubricants require to be further classified, blended and clarified, to produce the finished oil, the quality of which depends on the careful choice of raw material according to the specific purpose for which it is intended.

No " crude " yields a perfect lubricant for all purposes, and the art of the blender is to adjust the mixture to produce a " balanced " oil and to prepare the most suitable oil for various lubrication needs.

It is usual to classify the various types of oil according to the purpose for which they are intended as :—

Spindle Oil.
Light Machinery Oil.
Medium Machinery Oil.
Heavy Machinery Oil.
Motor Oils.
Dark Steam Cylinder Oil.
Pale Steam Cylinder Oil.

In each class there are various modifications for special purposes, for example—a spindle oil may be " non staining," a machine oil may have exceptionally low cold test (ice machine oils) or an engine oil may be " non emulsifying " and so on ; the object is always to produce a lubricant specially suitable for each particular purpose, and it will be realised that this is achieved not only by a knowledge of oil, but also as the result of an exhaustive study of engineering requirements.

THE TESTING OF LUBRICATING OIL IN THE LABORATORY

THE object of lubricating oil tests may be either to fix or specify a particular oil which has been found suitable in practice, so that subsequent deliveries shall be similar, or to determine the suitability of an oil for a given purpose.

There is some controversy as to the possibility of successfully accomplishing either of these aims since certain physical constants can be reproduced by oils of widely differing composition as a consequence of which the test is of doubtful value in foretelling the behaviour of the lubricant. With increasing technical knowledge, however, these disabilities are rapidly being overcome, and it is now quite practical to fix the properties of an oil within reasonably narrow limits provided a sufficient number of tests (variables) are taken and each figure correlated with the other. For example, a specification which gives only specific gravity, flash point and viscosity at one solitary temperature is quite useless to fix the composition of an oil, because these figures can be produced by numerous mixtures of totally different character, but if the viscosity at two or more temperatures is stated and such factors as cold test added, the range of blends which will meet the specification becomes narrower. The latest development is to include tests of a highly specialised nature such as accelerated oxidation, carbon residue, differential solubilities, emulsibility and " oiliness " factor. A study of the lubricant by these special means enables us to go far, not only in fixing the origin and degree of refinement of the oil, but also to foretell its practical behaviour in engines, with considerable accuracy.

The specific gravity of an oil is the ratio of the weight of a given volume of the oil to that of an equal volume of water.

$$\text{Sp. Gr.} = \frac{\text{Weight of given volume of oil.}}{\text{Weight of equal volume of water.}}$$

All liquids expand when heated so it is necessary when mentioning the specific gravity to state the temperature at which it is taken. It is usual to determine the gravity of engine oils at 60°F., or 15.5°C. and the ratio then should be expressed.

$$\text{Sp. Gr. } 60^\circ\text{F. } (15.5^\circ\text{C.}) = \frac{\text{Weight of given volume oil at } 60^\circ\text{F. } (15.5^\circ\text{C.})}{\text{Weight of equal volume of water at } 60^\circ\text{F. } (15.5^\circ\text{C.}).}$$

For convenience it is usual to take the specific gravity of solid lubricants at 212°F. (100°C.).

Sometimes the specific gravity of oil is referred to water at a different temperature and is then expressed as (say) :—

$$\text{Sp. Gr. } \frac{50^\circ\text{C.}}{15.5^\circ\text{C.}} = \frac{\text{Weight of oil at } 50^\circ\text{C.}}{\text{Weight of equal volume of water at } 15.5^\circ\text{C.}}$$

Now when water is cooled to 4°C., a given weight possesses the minimum volume and this is called the "maximum density" of water and at this temperature 1 c.c. of water weighs 1 gram.

If now we determine the weight of a given volume of oil at any temperature relative to the weight of an equal volume of water at 4°C. we get the "density" of the oil which is usually expressed as (say) :—

$$\frac{\text{D. } 15.5^\circ\text{C.}}{4^\circ\text{C}} = \text{Density of oil at } 15.5^\circ\text{C.}$$

The density is not used in commercial work but is of importance in the scientific study of oil.

Mineral lubricating oils increase in volume slightly when warmed, the increase per degree F. being on the average, 0.00035 of its original volume at any lower temperature; consequently it is easy to calculate the specific gravity at any temperature when it is known at some other temperature. It is sufficiently accurate for ordinary purposes to simply multiply the difference between the two temperatures in degrees Fahr. by 0.00035 and either add to or subtract from the known specific gravity according as the desired temperature is either cooler or hotter, e.g. :

> Sp. Gr. at 80°F. is (say) 0.9123—what will it be at 60°F. ?
> 80°–60° =20 ×0.00035 =0.007.
>
> As 60°F. is cooler than 80°F. we add 0.007 to the known Sp. Gr. 0.9123 giving 0.9193 at 60°F.
>
> The specific gravity of lubricating oils varies from about 0.865 to 0.945.

It is lowest for the thin Spindle Oils and rises with increase in the boiling point in any particular class of raw material.

The specific gravity bears no simple relation to any of the other physical properties of an oil, but is simply an indication of the chemical composition and natural source of the oil, but very little is known regarding the different compositions expressed in exact chemical language. Broadly speaking, the oils of low specific gravity possess viscosities which are not affected by temperature to so great an extent as oils of high specific gravity, so that very roughly, a knowledge of the specific gravity gives a hint as to the shape of the " Viscosity-temperature " curve.

The specific gravity is easily determined by means of a Hydrometer or, with greater accuracy, by weighing a known volume on a delicate balance.

For commercial purposes it is unnecessary to express the value to greater accuracy than three decimal places and a tolerance is generally allowed in the trade of plus or minus two points in the third decimal place when checking specifications or deliveries. That is, an oil specified as 0.900 may reasonably be anything between 0.898 and 0.902.

NOTE.

Farenheit—Centigrade Conversion Formulae :

$$°C. = (°F. - 32) \times \frac{5}{9}$$

$$°F. = (°C. \times \frac{9}{5}) + 32$$

FLASH POINT—FIRE TEST—VOLATILITY

When strongly heated, all mineral oils give off vapour. The temperature at which sufficient vapour is produced to give a mildly explosive mixture with air, is called the Flash Point.

When the oil is heated in a confined space in the presence of only a small amount of air, " flashing " takes place at a lower temperature than when the oil is heated in an open vessel in the air. The former is called the temperature of Closed Flash, and the latter the Open Flash.

If the oil is heated to a still higher temperature, vapour is given off sufficiently rapidly to keep the surface of the oil alight when a flame is applied. This is called the Fire Test.

The difference between the figures for Closed and Open Flash may be taken on a rough average as 20°F. for engine oils and 30°F. to 40°F. for steam cylinder oils.

Typical values for three classes of oil are :—

FLASH AND FIRE POINTS.

	Light Engine Oil.	Heavy Engine Oil.	Steam Cylinder Oil.
Closed	380°F. (194°C.)	405°F. (207°C.)	510°F. (266°C.)
Open	400°F. (204°C.)	425°F. (218°C.)	540°F. (283°C.)
Fire	450°F. (232°C.)	475°F. (246°C.)	600°F. (316°C.)

The fire test is about 50°F. above the open Flash for engine oils and 60°F. to 70°F. for steam cylinder oils.

These examples are worth remembering as they enable one to estimate the other two figures when one is known.

In the early days of the Petroleum Industry, Flash Point was an important test for the safety of an oil so far as fire risk is concerned, but nowadays refining is so perfect that a lubricating oil possessing a dangerous Flash Point is very rarely seen.

The loss in weight of an oil when heated for long periods of time is called its Volatility.

The Flash Point is not a measure of the volatility of the oil because it usually represents the vapour pressure of the most volatile constituent of the oil which may be only a minute fraction of the total bulk. For example, the addition of 1% of petrol spirit was found to lower the Closed Flash Point of an oil 20°F.

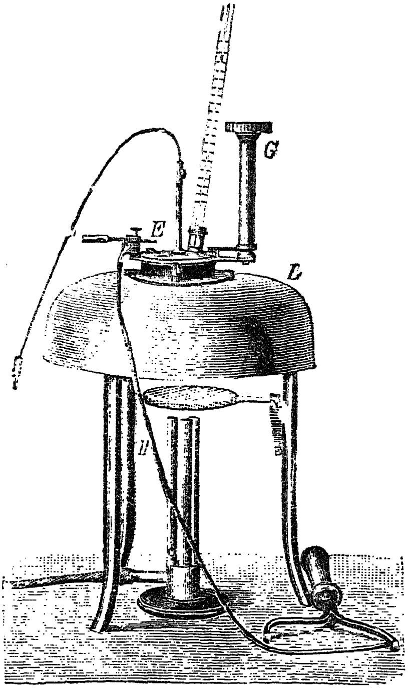


FIG. 1.

FLASH POINT APPARATUS (PENSKY-MARTEN).

but had no measurable effect upon the volatility at 350°F. The following example also shows very clearly that there is no simple relationship between the volatility and the Flash Point :—

	Oil " A."	Oil " B."
Closed Flash Point	402°F. (206°C.)	380°F. (194°C.)
Volatility at 370°F. (188°C.) for one hour	16.3	14.3

Likewise the Flash Point does not measure the ability of the oil to resist decomposition by heat and is in no way related to the carbonising or oxidising tendencies of the oil. A high Flash Point was once regarded by ill-informed people as a measure of the value of the oil for use in Internal Combustion Engines, but there is no evidence whatever in support of this view beyond the fact that a reasonable Flash Point is some indication of a well refined oil.

The Flash Point is generally determined by an apparatus designed by Pensky-Marten and in the trade a tolerance between various deliveries of plus or minus 2.5°F. is allowed. When determined at high altitudes a correction should be applied for the barometric pressure.

Occasionally a specification is seen asking for the " percentage loss in weight at a certain temperature for a given time." This is almost useless. The loss depends not only on the time and temperature but also on the volume of the oil, the shape of the containing vessel and the presence or absence of currents of air.

To be of any value this test must be carried out in a special apparatus called a VAPORIMETER which consists of a tube heated to a given temperature through which air (or steam) is passed at a given velocity. The oil under test is placed in a boat shaped dish of definite size which is introduced into the heated tube in such a way that the surface of the oil is exposed to the current of hot air or steam. Unless the Volatility Test is performed in this way the results are meaningless.

For example—if two dishes of oil, one rather volatile and one less so are heated side by side in an oven, the vapours of the more volatile sample will condense in the other and may even increase the weight of the latter.

Volatility Tests are more or less unnecessary because refining has recently been so highly developed that " volatile " matter is not left even in the commonest oils and the loss in weight proves to be no satisfactory measure of the lubricating value of the oil.

COLD TEST, CLOUD POINT, POUR POINT

The behaviour of an oil under conditions of extreme cold is of great practical importance.

In most engines and machines the lubricant is conveyed to the bearing by pipes and ducts, which are often in a more or less exposed place, and should the oil in these pipes tend to crystallise or freeze solid, the flow to the bearings and moving parts is impeded. Oils which freeze and precipitate readily also give trouble in handling — they cannot be freely pumped or poured from casks or containers.

A knowledge of the temperature at which oil will crystallise or solidify is, therefore, of great importance. Now unlike chemical compounds which suddenly solidify at given temperatures oils have not an exact and constant solidifying point: as the oil is cooled slowly, it first becomes thicker and thicker until a point is reached when any crystallisable matter, if present, will commence to precipitate. At this temperature the oil becomes dull and semi-opaque. This temperature is called the "CLOUD POINT."

On still further cooling, the temperature is reached at which the oil becomes frozen solid, and this is called the "COLD TEST" or "SETTING POINT."

At a temperature slightly above the final setting point the oil will just cease to flow when a vessel containing it is held in a tilted position for five seconds, and this point, which is of chief practical interest, is called the "POUR POINT."

The pour point is approximately 5°F. above the setting point.

There is considerable variation in these tests shown by lubricating oils according to their origin and degree of refinement. Considerable attention has been paid to this property by the refiner in recent years, and it may be said today that the majority of commercial engines and machinery oils will remain pourable down to the temperature of freezing water, namely, 32°F. (0°C.).

In earlier times, many lubricating oils contained paraffin wax, which crystallised at comparatively high temperatures, giving a "CLOUD POINT," but nowadays this wax is so well removed that the Cloud Test has no longer much interest.

The Cold Test is some guide to the origin of the crude oil. Paraffin base crudes yield lubricants of somewhat higher setting points than Asphalt base oils, and it may be stated that, on the average, the former have cold tests of −7°C. to −1°C. (18°F. to 30°F.) while the latter generally range from −18°C. to −7°C. (0°F. to 20°F.).

A few selected crudes by a special refining withstand temperatures as low as minus 20°F., but these are exceptional products used for refrigerating machinery.

Incidentally, the terms " Paraffin Base " and " Asphalt Base " are rather unscientific, but are commonly used to differentiate two broad divisions of natural crudes, according to the products with which they are associated.

Paraffin base crudes are those from which solid paraffin wax can be separated by heating and subsequent cooling, as distinct from those crudes which do not yield crystalline wax, but only an amorphous solid (Asphaltic Oils).

Oils of low cold test are obtained by refrigerating suitable crude distillates and then filtering off the precipitated frozen wax or solid under pressure, while the pasty mixture is still cold. The outflowing filtered oil will then remain clear and fluid at this temperature.

A very low cold test is no measure of the lubricating value of an oil, but it is desirable for practical reasons that general lubricating oils shall have a Pour Test of 30°F. or *slightly below*.

The oils of still lower Cold Test are not particularly to be desired, except in special cases and in very cold countries.

The Pour Test and Cold Test is determined by very slowly cooling a sample in a test tube immersed in a cooling liquid. The tube is removed at 5°F. intervals and held on its side for 5 seconds. That temperature at which it just ceases to flow is the " Pour " Point and the Cold Test is 5°F. lower than this.

In expressing the results, a tolerance of 2°F. is usual, i.e. an oil specified as Cold Test 25°F. is not refused if the Analyst reports 27°F.

VISCOSITY

One of the fundamentally important physical characteristics of lubricating oil is Viscosity, which is best defined as that property by which it resists a change of shape.

A quantity of liquid contained in an ordinary tumbler resting on a table will have a shape as in Fig. 2a, but if the glass be tilted, the liquid will be compelled to take a shape as in Fig. 2b.

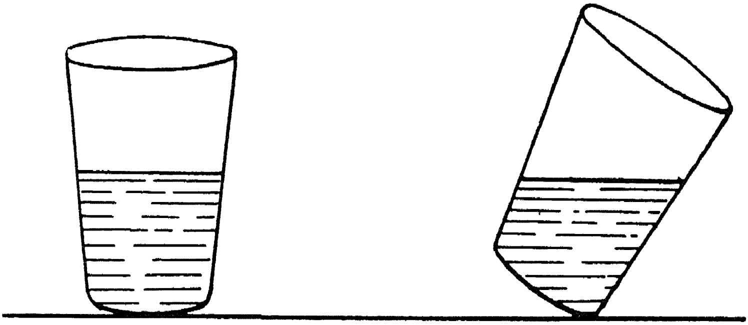


FIG. 2A. FIG. 2B.

SKETCH SHOWING CHANGE OF SHAPE OF A LIQUID IN A GLASS WHEN TILTED.

If the liquid is water, this new shape will be assumed almost immediately the tumbler is tilted, but if thick oil is contained in the glass, the change of shape of the liquid may take some seconds.

The " measure " of viscosity is the " time " taken to effect a change of shape, and we shall see later that the resistance is of primary importance in lubrication because it results in the formation of wedge-like oil films between bearing and shaft which are not readily " deformed " by pressure or shock, i.e. change of shape of the wedge-like film takes measurable " time."

Viscosity manifests itself in many ways—it impedes the motion of a ship in water or of the flow of a liquid in a pipe and this latter effect being the simplest thing to measure, is largely used in the quantitative determination of Viscosity.

Poiseville originally deduced a formula connecting the various factors which influence the rate of flow of a liquid through a pipe or from an orifice. His classic formula for a liquid flowing from a vertical pipe is :—

$$\eta = \frac{\pi g d h r^4 t}{8 V l}$$

η = coefficient of viscosity.
g = Gravity constant.
d = density of liquid.
h = mean head liquid column in tube.
r = radius of bore in tube.
t = time required for a volume V to flow out.
l = length of the tube.

When all the above factors are given in the C.G.S. system of notation, the value of η is called the coefficient of "absolute viscosity."

It is important to note that the time taken for a given volume to flow is proportional to the viscosity and the fourth power of the radius of the tube.

The unit of viscosity (i.e. the coefficient) is the force required to move a plane surface 1 sq. cm. in area at a speed of 1 cm. per second over another fixed and parallel plane, the space of 1 cm. between the planes containing the fluid. This force is measured in dynes.

It has been decided by the British Engineering Standards Committee to call this C.G.S. unit, the POISE and for liquids of low viscosity one hundredth part of this, the CENTIPOISE is used.

The viscosity of an oil changes rapidly with temperature and further reference will be made to this.

The effect of viscosity shows itself often as though the liquid were possessed of friction which hindered the passage of one particle of the liquid over another and many writers refer to viscosity as "Internal Fluid Friction" but this description of the phenomenon is not strictly accurate although it is a useful expression which conveys an impression of the effects which viscosity can manifest in lubricating practice. For example, the "internal friction" of the oil gives rise to heat when a thick film of oil is kept in rapid motion between bearing surfaces, etc.

The viscosity of various lubricating oils varies enormously from thin spindle oils which are only a few times the viscosity of water to thick viscid liquids used for highly superheated steam cylinders.

All the fatty oils with the exception of Castor are relatively thin and Rape Oil owing to the constancy of its composition, has been used as a standard of reference, but this system of viscosity notation is disappearing and it is more usual to give figures representing the number of seconds taken for a given volume to flow from a standard orifice, or best of all, the absolute viscosity in dynes or poises.

The following section deals with the measurement of viscosity.

VISCOSITY MEASUREMENT

The most convenient way to determine the viscosity of an oil is to note the time taken for a given volume to flow from an orifice whose diameter is accurately known, and this method is universally used in commercial viscometry.

There are a number of instruments for the purpose named after their inventors: in Britain the usual viscometer is the Redwood, in U.S.A. the Saybolt and in Europe the Engler. All these instruments are similar in principle and consist essentially of a cylindrical vessel into which the oil is filled to a certain level. The bottom of the vessel has a fairly fine hole or short narrow-bored tube of agate or hard steel which is closed with a plug.

The oil vessel is enclosed in an outer jacket in which either water or oil can be heated to maintain a constant temperature. The sample of oil contained in the inner vessel is brought to the required temperature and the plug is then removed, allowing

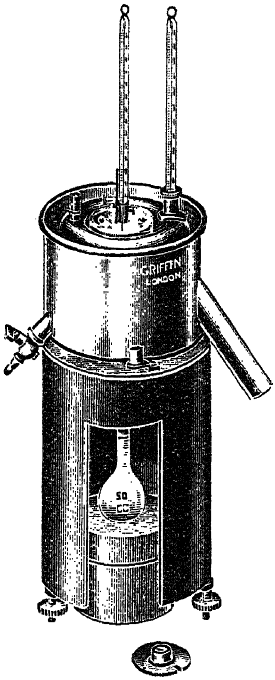


FIG. 3.
REDWOOD VISCOMETER.

the oil to flow out into a graduated receiving flask where a fixed quantity is collected and the time in seconds noted for this amount of oil to flow into the flask.

In Redwood's Viscometer the time taken to collect 50 c.c. is noted, in Saybolt's 60 c.c. and Engler takes 200 c.c.

It must be noted that all these Viscometers give simply relative figures, each instrument being standardised by making slight adjustments to it until a liquid of known viscosity runs out in a certain number of seconds.

To determine the " Absolute Viscosity " a special U tube containing a fine capillary is used, known as the U tube Viscometer.

> The U tube viscometer (Oswald pattern) has been adopted by the British Engineering Standards Committee as the most reliable instrument for the determination of Absolute Viscosity.

For very simple, quick measurements, mention must be made of Michell's viscometer, which consists of a steel ball pressed in to a cup on which are three minute projections. A few drops of the oil are used to moisten the cup, and the ball is then placed into position. On lifting the handle attached to the cup, it is found that the ball takes a few seconds to fall away and this time in seconds divided by a constant for the instrument gives the viscosity.

Viscosity figures on the Redwood Scale represent simply the number of seconds taken for 50 c.c. of oil to flow from the standard instrument at the given temperature, e.g. 850 seconds at 100°F. (38°C.). Saybolt figures are the number of seconds for 60 c.c. outflow. Engler expresses the results as " Specific Viscosity " which is the number of seconds required for the flow of 200 c.c. divided by the time taken by an equal volume of water.

CONVERSION FORMULAE.

To get approximate values of Absolute Viscosity from Redwood figures :

$$\underset{\text{(POISES)}}{\eta\ \text{(absolute)}} = D\left(AR - \frac{B}{R}\right)$$

D = density of the oil at *given* temperatures.
R = Seconds Redwood.
A = .0026
B = 1.7.

$$\frac{\text{Redwood}}{29} = \text{Engler Value.} \qquad \frac{\text{Redwood}}{0.85} = \text{Saybolt Value.}$$

$$\text{Engler} \times 29 \quad \text{Redwood.} \qquad \text{Saybolt} \times 0.85 = \text{Redwood.}$$

All these formulae give only approximate relationships.

Farenheit—Centigrade Conversion Formulae :

$$°\text{C} = (°\text{F.} - 32) \times \frac{5}{9} \qquad °\text{F.} = (°\text{C.} \times \frac{9}{5}) + 32$$

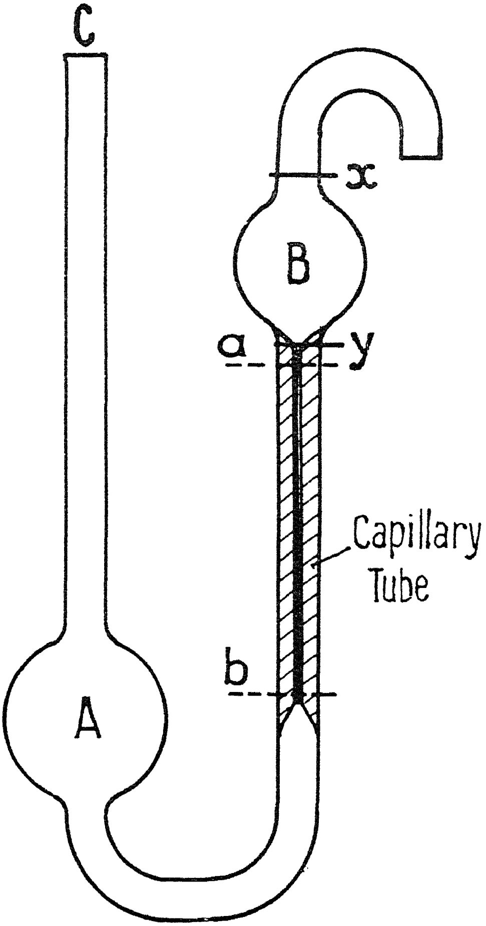


FIG. 4.

Shows a simple form of the apparatus.

U TUBE VISCOMETER.

A given volume of oil is introduced into the larger bulb A through the limb C and this is sucked up into the bulb B.

The level is adjusted at x and when the desired temperature is reached the oil is allowed to flow through the capillary tube a b, until the level has fallen to y. The volume of oil in B between x and y being known and the number of seconds required for the flow of this volume through the capillary it is easy to calculate the absolute viscosity.

In accurate measurements the density of the oil should be taken into account, but this is rarely done in commercial work, so that the figures are not strictly accurate, e.g. an Oil of 1,000 seconds Redwood is not necessarily just twice as viscous as one giving 500 seconds.

Redwood figures are only comparable at medium thicknesses and viscosities of (say) 3,000 seconds are quite unreliable. The instrument is most accurate for a range of viscosities from about 50 up to 2,000.

A tolerance is usually allowed on specification of plus or minus 2% unless special remarks are made to the contrary.

When taking viscosities the temperature of the oil must be maintained absolutely constant and accurate; one quarter of a degree centigrade will materially change the number of seconds on a Redwood or other viscometer and disagreements frequently arise from this source.

THE EFFECT OF TEMPERATURE ON VISCOSITY

All liquids become thinner when heated, and in the case of oils this reduction of viscosity with temperature is very marked and has important consequences in lubrication.

The thickness of the oil-film which separates a shaft from its bearing is proportional to the viscosity of the oil for any given set of conditions, and it is essential that the oil shall remain thick enough under all circumstances to keep the metallic surfaces sufficiently apart.

On the other hand, too high a viscosity is undesirable, because it causes the oil flow to be sluggish and renders it difficult to get a sufficient " feed " to the moving parts besides causing excessive resistance to motion.

It is clear that all other things being equal, the best oil will be that which has a viscosity which changes least with increase of the working temperature ; and, as a matter of fact, lubricating oils differ considerably in their viscosity-temperature variations.

Oils made from certain Pennsylvanian crudes of low specific gravity retain their viscosity at elevated temperatures better than the high gravity oils of Western America.

Oils from the Russian fields are intermediate between the Pennsylvanian and Western types in this respect.

In the manufacture of " GERM " oils, care is taken to select oils of good viscosity-temperature properties, and they are superior to the majority of well-known brands on the market—for example :—

Approximate Viscosity.	Brand A.	Brand B.	"Germ" Motoil M.H.
Redwood 70°F. (21°C.)	1,800 seconds	1.800 seconds	1,800 seconds
,, 140°F. (60°C.)	158	152	170
,, 200°F. (93°C.)	53	52	57

A further important property of the " GERM " oils is that they maintain superior lubricating properties even when quite thin, owing to the influence of the " GERM " on the friction.

Oils which are very thick and stodgy when cold are undesirable not only because they " feed " badly, but excessive " drag " is put on the moving part by the viscous friction : this results in a rise of temperature of the bearing surfaces until a point is reached where the oil is reduced sufficiently in viscosity to give minimum friction. This limiting temperature will be lower with oils which are thoroughly fluid and mobile in the cold and yet preserve good viscosity when warm.

Some ill-informed buyers like an oil to "look thick" in the bottle or cask when cold, because they think that this means that it will always be viscous when heated, but this view is obviously incorrect.

For automobile lubrication an oil of good viscosity-temperature curve is very desirable, since by this means easy starting is ensured and efficient lubrication of the hot engine secured.

At very high temperatures—such as are met with in superheated steam cylinders, the viscosity of all oils come close together, as was originally pointed out by Henry M. Wells and W. S. Taggart ("Cylinder Oil and Cylinder Lubrication"). The viscosity temperature gradient of steam cylinder oils is therefore of less importance, except in so far as it is an indication of other properties of the oil.

The difference in viscosity-temperature gradient shown by oils of various types is clearly shown in the figures given in the table on page 67.

THE CARBON RESIDUE OR COKE TEST

When a lubricating oil is strongly heated a portion boils away as vapour and the remainder decomposes into gases and carbonaceous matter. The amount of "cokey" matter left behind depends on the conditions of the experiment. If the residue is very strongly heated in a large excess of air all the carbon burns away and nothing is left but the mineral ash, but moderate heating in the absence of excess air leaves the carbon unconsumed.

In order to obtain comparable results it is necessary to carry out the test under definitely prescribed conditions and two methods are now in use, namely, Conradson's Method and Ramsbottom's Coke Test.

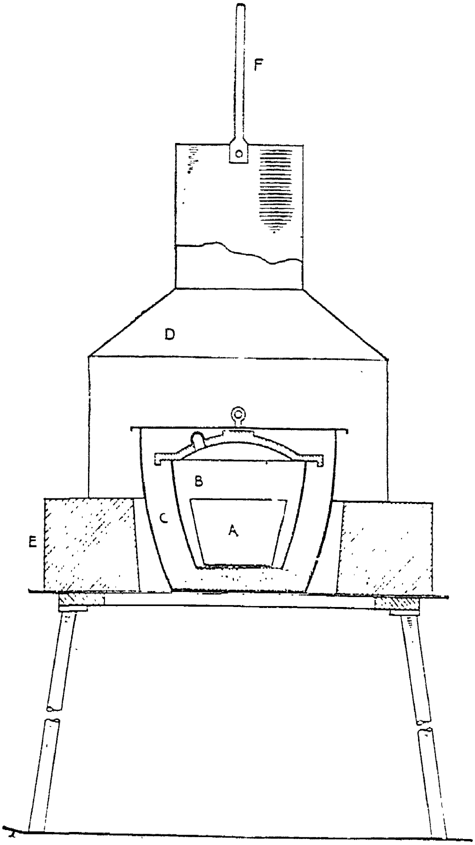


FIG. 5.
CONRADSON CARBON TEST APPARATUS

In the Conradson process the sample is heated in a crucible which is enclosed in another and larger iron crucible which is again surrounded by a muffle of definite size and shape. The heat is applied by a standard gas flame and continued until fumes are no longer emitted. The weight of " coke " left behind per 100 parts of oil is called the Conradson Coke Value, or Carbon Residue.

In the Ramsbottom method the oil is introduced into a glass bulb of fixed size and shape, which is then plunged in molten lead at exactly 550°C., until all fuming ceases. The percentage of residue in the Ramsbottom test is generally smaller than in the Conradson test. The practical value of either of these tests is doubtful and they can only be considered in relation to other tests of the oil. For example—an oil is sometimes found to give a very low Coke Test when clean and unused, but quickly develops a high coke figure after oxidation or use in an engine. It is also a remarkable fact that many high grade Pennsylvanian oils of low specific gravity and good viscosity temperature coefficients give somewhat higher coke figures than the Texas or Mid-Continent Oils of poor viscosity-temperature coefficient and relatively weak chemical stability towards oxidation.

In this sense it is seen that an exceptionally low coke figure is not necessarily a measure of a good lubricant. The coke figure is influenced by the nature of the crude and the extent of the refining: it increases with the viscosity of the oil of any given class being very low for Spindle Oils, which just boil away, and highest for Black Steam Cylinder Stocks.

A rough average given by oils of differing viscosity is :—

	Conradson.
Spindle and Light Machine Oils	0.05 to 0.15
Medium Motor Oils	0.2 to 0.5
Heavy Motor Oils	0.3 to 0.9
Pale Steam Cylinder Oil ..	0.9 to 1.5
Dark Steam Cylinder Oil ..	1.8 to 3.5

The Ramsbottom figures are lower than these but bear no direct relation.

Further reference will be made to the carbon residue test when discussing " oxidation."

OXIDATION OF OIL

Lubricating oils consist chiefly of compounds of carbon and hydrogen which are called hydrocarbons and when these bodies are violently churned up with the oxygen of the air a certain amount of chemical combination takes place resulting in the formation of quantities of oxidised hydrocarbons and sometimes of decomposition products. The mild oxidation of complicated hydrocarbons occurring in lubricating oil has been extensively studied in the laboratory but so complex is the composition of lubricating oil that our knowledge of the chemical reactions involved still remains very meagre. Two distinct effects of oxidation are however recognised: on the one hand certain hydrocarbons can be broken up into bodies of lower molecular weight, accompanied as a rule by the formation of faintly acidic matter and on the other hand, the oxygen can combine with the hydrocarbons forming unstable addition products which presumably then commence to combine with each other forming compounds of higher molecular weight, which are insoluble in the oil and may be of a gummy or actually solid carbonaceous nature. According to the kind of hydrocarbon present one of the reactions may predominate, but in every case the two effects go side by side, and for the lubrication engineer the nature of the oil after prolonged oxidation is the only thing of importance.

In this respect there is a most wide and marked difference between oils of various classes according to their origin and degree of refinement, some breaking down into highly acid products while others increase in viscosity and produce insoluble sludge.

The darkening of lubricating oil in use is partly due to oxidation and in the early stages the oxidised matter remains soluble in the oil, but as time goes on the quantity increases and ultimately deposits on the metal walls of the engine. The rate at which this objectionable sludge is formed depends on many factors some of which greatly accelerate the reaction (*Catalysts*) but it is possible to produce oils which resist this oxidation to a remarkable extent and remain clean and bright for long periods.

This is achieved by choosing a suitable crude and highly refining it until only the more stable pure hydrocarbons are left.

From natural petroleum the most stable crudes are obtained in the Eastern States of the United States of America, then intermediately come Russian Oils and worst are those of Western America and certain other fields, but it is possible to effect improvement in stability by special methods of refining.

SLUDGING AND THE OXIDATION OF LUBRICATING OILS

In the crank case of automobiles and all kinds of enclosed engines the oil is continually churned up in the presence of air and moisture at fairly high temperatures, as a result of which the oxygen of the air acts on the oil tending to decompose it by a process of oxidation, and it is found that oils differ very much in their ability to resist this effect.

Particularly in circulating systems the influence of oxidation on the oil is of the greatest importance and the need for resistance to this reaction cannot be over emphasised.

Excessive oxidation results in thickening of the oil and the formation of objectionable carbonaceous deposits and even corrosive matter.

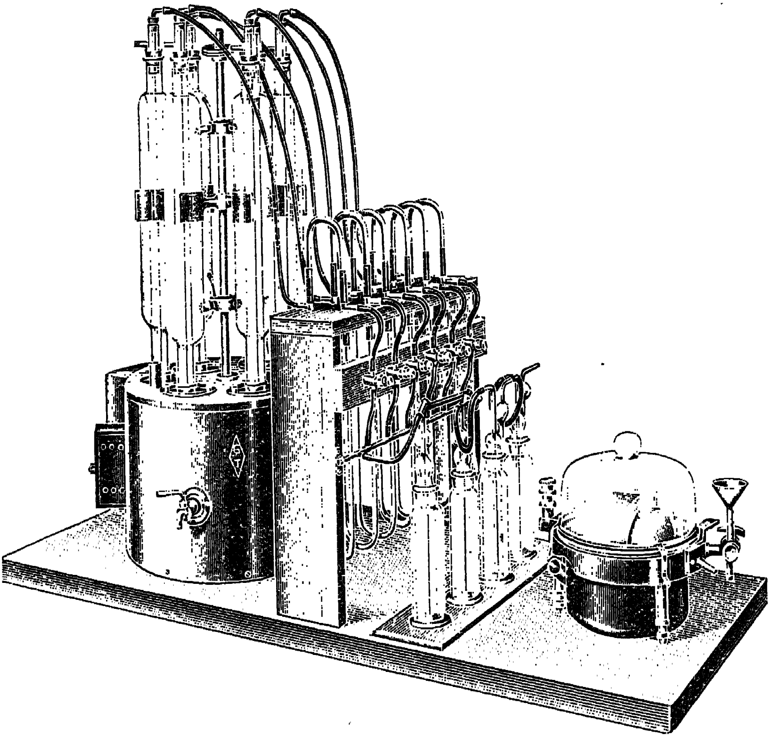
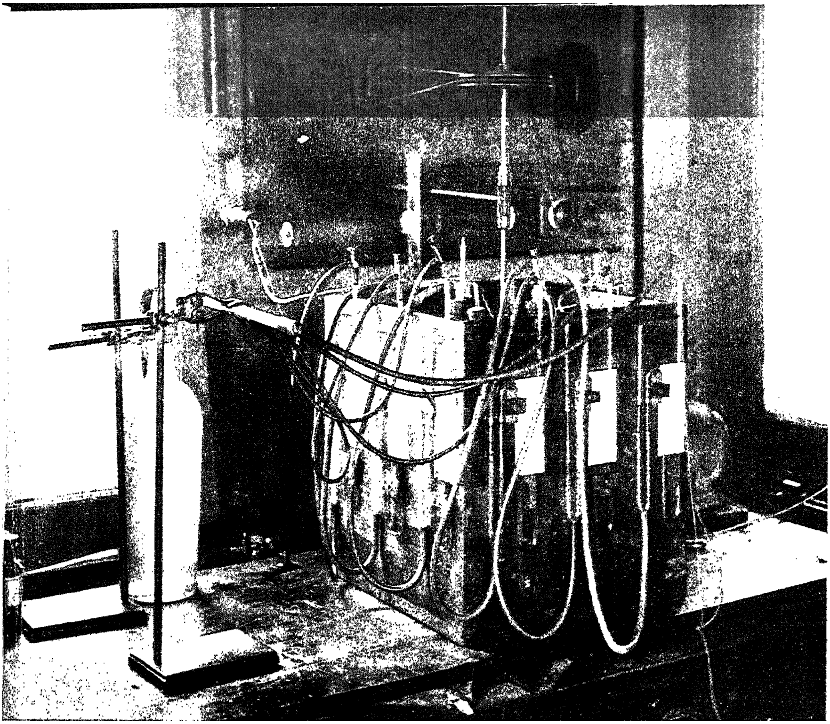
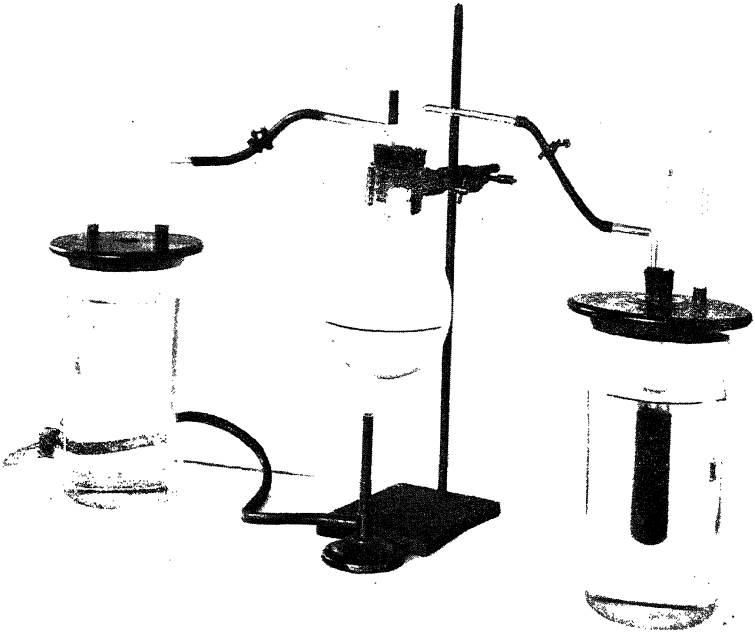


FIG. 6.
SLUDGE TEST APPARATUS (MICHIE).



ELECTRICALLY CONTROLLED APPARATUS
FOR STUDYING THE OXIDATION OF OILS



STANDARD METHOD FOR DEMULSIBILITY TEST
(Institution of Petroleum Technologists)

Closely connected with oxidation is the stability of the oil to decomposition by heat; a badly oxidised oil is broken up comparatively easily by the hot piston and yields an excessive amount of carbon residue.

The most recent development of laboratory methods is the "oxidation test." A known volume of oil is placed in a tube contained in a hot bath at a fixed and accurately maintained temperature while a measured volume of air is slowly bubbled through the sample for a number of hours.

Under these conditions the oil rapidly darkens and thickens, and the change in viscosity, carbon residue value, and other properties is noted, the best oil being that which changes least. Three important modifications of this test are now established:—*the* Verteerungszahl *of the German Standard Methods, the Michie* test, and the British Air Ministry Oxidation Test.

In the latter method 40 c.c. of oil is heated for 12 hours at 200°C. while 15 litres per hour of air is bubbled through the sample. The increase in viscosity is noted and expressed as the ratio of final viscosity to original, e.g. if the unoxidised oil has a viscosity of say 1,000 and the oxidised is found to be 2,500, the viscosity increase ratio is $\frac{2,500}{1,000}=2.5$.

The Ramsbottom (or Conradson) Carbon Residue Test of the oil is also compared with the value for the oxidised sample which is always much increased.

The following table shows the difference between three typical Commercial Motor Oils when submitted to this test and it is noteworthy that the sample which gives the lowest Carbon residue in the pure unoxidised state may rise to a very high value after oxidation.

Oil.	Ratio of Viscosity after Oxidation to original Value.	Conradson Carbon Test. Orig. Oil.	After Oxidation.	Appearance of Oxidised Oil.
A.	2.0	0.4	1.9	Clear dark brown.
B.	3.5	0.8	3.4	Dull black gritty.
C.	17.0	0.2	3.5	Black jelly-like mass.

Sample C. while giving a very low Conradson Carbon originally has thickened to seventeen times the original viscosity.

There can be no doubt but that the chemical stability and resistance to change of an oil is measured by such oxidation tests but nevertheless there is some controversy regarding the value of such tests as applied to engine lubrication.

Trials carried out on engines have shown in some cases that there is a good relationship between the laboratory results and the behaviour of the oil in engines but it must be mentioned that experiments which do not completely support this view have been published. At least it can be said that oils which show up well in this test will behave satisfactorily in I.C. engines although the reverse may not be strictly true. Tests of oil from an engine sump after extensive service show that the Carbon Residue value of the used oil is roughly what one would expect from the figures given by the laboratory oxidation test—a few examples are given :—

		Carbon Residue.	
Oil.	Orig. Oil.	After Oxidation.	Used in an engine.
A.	0.29	2.08	After 1,500 miles in an automobile. 2.2
B.	0.21	3.2	After 1,800 miles in an automobile. 3.4
C.	0.5	2.5	After 350 hours in a Diesel engine. 2.8

The following table gives the results of this test on a few representative oils.

Oil.	Grade.	Viscosity increase. Ratio after Oxidation.	Carbon Residue.	
			Before.	After.
A.	Medium Heavy Motor Oil	2.03	0.29	2.08
B.	Ditto	3.0	0.15	2.4
C.	Ditto	15.0	0.21	3.2
D.	Heavy Motor Oil	2.9	0.86	3.8
E.	Ditto	2.3	0.64	2.7
F.	Diesel Engine Oil	1.85	0.3	1.8
G.	Ditto	2.1	0.2	2.0

TRANSFORMER AND TURBINE OILS.

This class of oil needs to be particularly resistant to oxidation and a modified oxidation test is generally used to examine them. In this method the temperature is lower than that previously described and a strip of copper is immersed in the oil which is heated for 70 hours in a current of air (Michie's Test).

A further modification is used by Weiss and Saloman who have recently conducted most extensive researches on this subject. These authors are studying the " Mechanism " of sludge formation from the purely scientific angle and the reader is referred to their original papers for a detailed account of the present state of knowledge on this most important subject.

THE DEMULSIFICATION NUMBER

Lubricating oil in turbines and enclosed steam engines frequently is churned up with water or condensed steam and it is essential that the two liquids do not mix to form a persistent troublesome emulsion.

A good oil will quickly separate again from water, which has accidentally been mixed with it, when allowed to stand for a short time. The simplest and most direct way to observe the behaviour of a sample of oil in this respect is to violently mix measured quantities of oil and water at a given temperature and then allow the mixture to stand undisturbed, and note the time taken for the water to separate from the oil. The mixing can be done by a motor driven stirrer and the process is recommended in America by Herschel and in England by the Admiralty.

In Herschel's method 20 c.c. of oil is violently stirred with 40 c.c. of water at 55°C. for five minutes. The mixture is then allowed to stand and a reading taken every minute of the amount of water which separates. Observations are taken over an hour and the amount separated in any given time multiplied by 60 and divided by the number of minutes since the stirrer was stopped is called the Herschel demulsification value.

The Institution of Petroleum Technologists use another method—20 c.c. of oil is placed in a graduated tube and steam is led into the oil until the total volume of oil and condensed water is 40 c.c. The steam is then shut off and the tube allowed to stand in a bath at 200°F. The number of minutes required for complete separation of the water is called the I.P.T. demulsibility number.

A good oil should separate completely in less than five minutes. These tests when applied to pure oil are of little value because they do not tell us what will happen when the oil has been in use for long periods. Some oils which quickly separate in a fresh state begin to decompose after a few weeks circulation in an engine and may then form troublesome emulsions. The demulsibility number should always be considered in relation to the sludge or oxidation test.

"OILINESS" AND ITS MEASUREMENT

The most recent advance in the technology of lubrication is the "oiliness" test.

In its simplest form this consists in measuring the friction between two polished surfaces of metal between which is a thin film of the oil under test (figure).

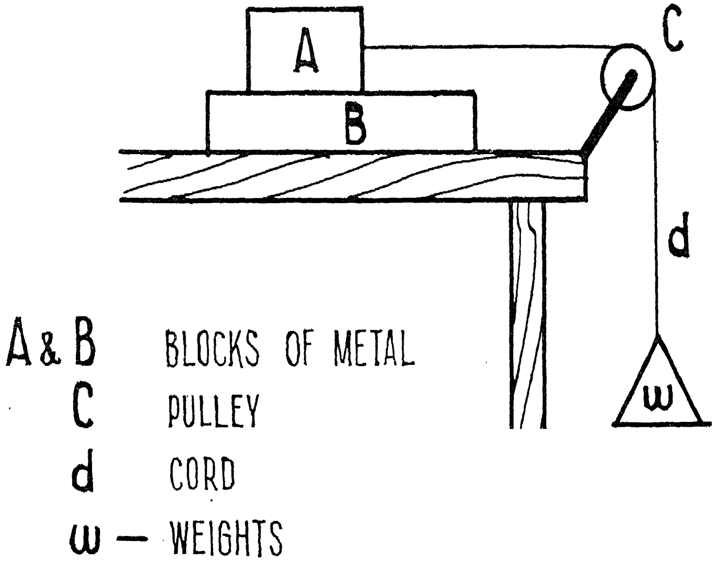


FIG. 7.

SIMPLE DEVICE TO MEASURE FRICTION.

If a heavy block of metal A, of weight W, rests on another slab B, and a weight *w* is applied to a cord attached to A over a pulley C, it is found that the block A will not move over the surface B until a certain definite weight is applied to the cord.

The minimum weight which will just cause the block A to move is a measure of the static friction between the two metals and if we divide this weight *w* by the weight of the block W we get the coefficient of static friction which is usually designated by the Greek symbol μ. For example if the weight of the block is 5 lbs. and 2 lbs. is required to be applied to the cord to move it then μ (coefficient of static friction) =

$$\frac{w}{W} = \frac{2}{5} = .4$$

If the metals are perfectly clean and dry this friction is very high but a trace of oil or grease on the metal lowers it appreciably. The " oiliest " oil is that which reduces the friction the most. It must be clearly remembered that the film of oil between the surfaces in these tests is almost infinitely thin and the remarkable fact is that in this condition of " boundary " lubrication the friction is proportional to the load or pressure squeezing the surfaces together, and as a result the coefficient of friction is almost independent of the load. In fact, we can define *true* " boundary " friction as that state in which the coefficient *is* independent of the load, for example :—

Weight of block. W (lbs.).	Weight required to cause slip w (lbs.).	Coefficient of Friction $\frac{w}{W}$
5	1	0.2
10	2	0.2
20	4	0.2

This coefficient varies not only with the oil but also with the contacting metals being different for say bronze on steel as compared to cast iron on brass. The static friction is measured by the force required to cause slip or motion from rest but once movement has started, the force required to keep it going is called the kinetic friction : this usually has a somewhat smaller value than the static.

There are now several delicate and elaborate instruments for measuring the static and kinetic friction. Some of the most careful measurements have been made by Paul Woog and the table gives a few of his results. We might call the reciprocal of the friction (i.e. $\frac{1}{\mu}$) the " oiliness " value or lubricating efficiency of the oil.

Oil.	Static coefficient.	Oiliness Value $\frac{1}{\mu}$
885 Pale	0.17	5.9
H.V. Pale	0.16	6.2
Bayonne Engine	0.16	6.2
" Germ " oil : 885 Pale + $\frac{1}{2}$% Stearine	0.10	10.0

Recently J. H. Wells has measured the kinetic friction up to 200 ft. min. at 110 lbs. per square inch at 60°C. His results are:—

		Oiliness Value $\frac{1}{u}$
Mineral Oil	0.118	8.4
" GERM " oil of identical viscosity	0.08	12.5

Vigorous research is being carried on towards the perfecting of instruments for determining " oiliness " and already verv
factory machines have been designed by Deel
schel, and Wells.

The technical staff of the Henry Wells Oil Co. Ltd., have for some years been working on this subject and have now succeeded in designing a small portable machine for testing the " oilines
of lubricants. The mechanical details of this machin
in a special pamphlet.

s " of lubricants varies widely but as a generalisation it is found that super-refined oils like toilet paraffin, transformer and certain turbine oils are sadly deficient in " oiliness."

The majority of pure mineral oils are not much superior but the animal and vegetable oils show a marked superiority. " GERM " oils made on the Wells-Southcombe process stand in a class by themselves and show the highest degree of " oiliness " and lubricating efficiency yet attained. This fact is no longer in dispute, the very accurate work of the British National Physical Laboratory and the American Bureau of Standards having established it beyond doubt.

T
elucidated by Herschel at the
ureau of Standards that the lubricating film is maintained and the advantage of the Wells-Southcombe process seen at bearing pressures up to many thousands of pounds per square inch.

Perhaps the most valuable observation recently made is that the " oiliness " property is maintained at comparatively high
ls and we have reason to state that under conditions where
film lubrication
the

CHEMICAL IMPURITIES

Mineral lubricating oils when properly refined consist essentially of pure hydrocarbons but there are traces of certain impurities usually present. These can be sulphur, nitrogen, ash, mineral or organic acidity.

Refinery technique is nowadays so developed that sulphur, nitrogen, and ash occur to only a negligible degree in all well refined oils.

Lubricating oils must always be quite free from mineral or corrosive acids but a trace of organic acid is usually found.

In the Wells-Southcombe process the oil is treated with a minute amount of the higher fatty acids and " GERM " oils give a small titratable figure but this material possesses no corrosive action.

It is not unusual to find a small percentage of organic acid in a mineral oil which has been in use in an engine for some time and these acids may even cause some pitting of the shaft or bearing if they are of an active nature.

Some millions of gallons of " GERM " oils have been used in engines all over the world without developing corrosive tendencies.

THE COLOUR OF LUBRICATING OILS

Mineral lubricating oils vary in colour from a pale straw yellow to deep red and in the case of steam cylinder oils, brownish-black.

It is important to distinguish between the colour by transmitted light and the colour by reflected light.

By the former, colour is not very important, extreme paleness being no guide to quality as a lubricant although it indicates a high degree of refinement. Much has recently been achieved in the production of super-refined pale yellow oils from most unpromising crudes but the general properties of the raw material appear to manifest themselves again after a short time in use, the super-refined oil tending to revert to the state of the less refined quality.

By reflected light the colour of an oil gives some guide to its composition—a blue fluorescence indicates oil of asphaltic origin imperfectly refined, while a greenish tone is usual with oils of Pennsylvanian type. The presence of filtered cylinder stock in a mixed oil generally produces a blend which is red to transmitted light and green to reflected light if the constituent oils are well refined.

In general, oils which are blue to reflected light are less stable towards oxidation than those of green shade.

Dark steam cylinder oils vary from greenish-black to brownish-black and even jet black, the latter being of poorer type.

The colour of an oil can be exactly specified by referring it to the colour of a glass screen of similar colour. In Lovibonds tintometer there is a series of coloured glasses, each colour and combination being numbered.

When viewed by reflected ultra-violet light from a mercury arc mineral oils show intense fluorescence and this method is sometimes employed to detect the adulteration of vegetable and animal oils by mineral.

When judging the colour of an oil the north light must be used and sunlight is to be avoided. The blender is always careful to reproduce a similar colour in deliveries, but the use of better refining methods tends to produce somewhat paler oils than previously supplied.

In the foregoing pages a brief account has been given of the various tests which are now applied to lubricating oils from which it will be gathered that a very comprehensive study can be made by a laboratory equipped with the necessary specialised apparatus. Old fashioned tests have been superseded and new methods of infinitely greater value have been developed to an extent which is rarely appreciated by the oil consumer. Above all it should be emphasised that an oil cannot possibly be judged by one, two or even three kinds of test, but the application of a variety of special tests each correlated with the other provides a very clear picture of the quality of the oil for any particular requirement. The application of the various properties of oil to engineering practice will now be considered.

For note on colour of reclaimed oils, see page 65.

THE GENERAL PRINCIPLES OF LUBRICATION

HOW OIL LUBRICATES

It is common knowledge that lubricating oil is used to keep bearing surfaces apart and so permit of easy running and reduced wear and tear. This result is brought about by forming a film or layer of oil between bearing and shaft which prevents metallic contact of the parts. but the question may be asked: " How does the oil form this film and what are the special properties which cause it to remain in the bearing under heavy pressure and high speeds? " These questions have occupied the attention of engineers, mathematicians, and physical chemists for years.

The first point to notice is that there must be a certain space between the shaft or " journal " and its bearing, or between the piston and its cylinder, into which the oil can get, and this space has to be of definite size in all well-fitted bearings. In engineering language, the diameter of the shaft must be less than that of the bearing in which it rotates, and this difference in diameter is called the " clearance." This " clearance " is of supreme importance to the running and durability of the bearing and for a shaft of one inch diameter it is roughly one and a half thousandths of an inch—a shaft measuring one inch in diameter requires a bearing bored to about 1.0015. It is in this minute " crack " that the oil has to remain and do its work although pressures of 200 to 300 lbs. per square inch are striving to dislodge it. Against this high pressure the ordinary oil-pump feed of 10-20 lbs. per square inch is insignificant, and indeed, as we know, the film withstands these high pressures in the absence of any feed pump in splash lubrication systems. How, then, is this film maintained? It is because the motion of the shaft acts like a pump producing its own oil pressure.

Fig. 8 represents in an exaggerated way the relationship of the journal to the bearing.

When the engine is at rest the shaft is in contact with the bearing in the line of the load, and around this contact line the oil is built up in a wedge-shaped manner. Immediately rotation begins, the shaft tends to climb up the side of the bearing, squeezing the oil along the arc, A B, but owing to that property of the oil called viscosity, the squeezing out takes time and the point X on the shaft has moved over to C before the oil at B has been brushed away. Now it is seen from the figure that owing to the eccentricity of the shaft there is a considerable space at C for the oil to be retained and that there is no pressure to be supported at this point. The shaft continuing its rotation, drags this oil from C with it and carries it round to A B, where it is again compressed, and so on each revolution. The result is that the oil along A B is under gradually increasing pressure and then from B to C the pressure is falling and may become actual suction in the neighbourhood of C.

If we bore a number of fine holes around the circumference of the bearing and connect these to pressure gauges, we can measure the pressure in the oil film at various points relative to the line of the load, and it is found that the greatest intensity of pressure occurs just beyond the load line and in this neighbourhood the shaft is forced very close to the bearing, see Fig. 8*b*. This is called " the point of closest approach " and it is essential that this distance shall not be too small or metallic contact will take place. As a matter of fact, in a well-made bearing this distance can be so little as one ten thousandth of an inch without danger to the running. When revolving, the shaft always remains eccentric to its bearing and this is the cause of the pumping action. The relationship of the shaft to the bearing with variations in viscosity of the oil, speed and loading, have been the subject of a great amount of elaborate mathematical study, and equations have been evolved connecting these variables and it is found that the theoretical

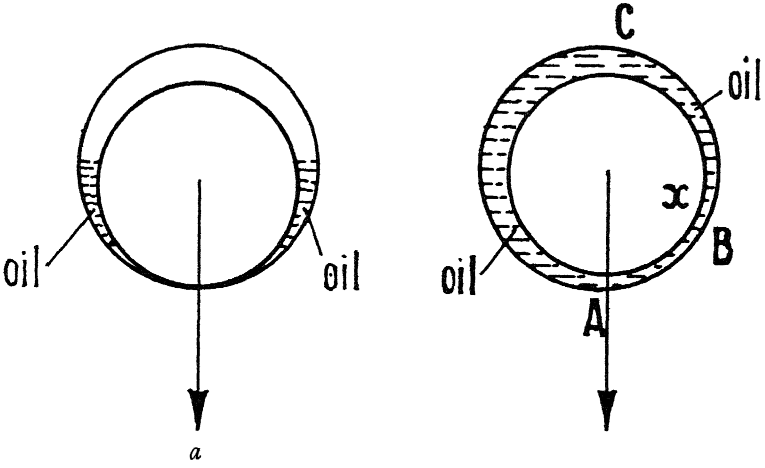


FIG. 8.

HOW OIL LUBRICATES.

THE SHAFT IN DIAGRAM B IS ROTATING COUNTER-CLOCKWISE.

conclusions are satisfactorily in agreement with practical observations so long as the shaft is moving at moderate speed. With any given oil the clearance at the point of closest approach becomes smaller with heavier loading or by diminished speed and when these factors exceed a certain value the film becomes too thin to keep the surfaces properly apart and a condition arises which has been called " semi-fluid " or " boundary " lubrication, as distinct from the fluid film type just described. When this state of affairs happens, as it very frequently does, the lubrication is no longer solely a function of viscosity but is largely dependent on a peculiar property of the oil to which the term " oiliness " has been given.

The precise explanation of this peculiar property of oiliness involves considerable knowledge of molecular physics, and it is intended only here to give a rough outline of recent views on this subject. It used to be thought that the resistance to sliding of two solids in contact was due to the comparative roughness of their surfaces—little projections knocking against each other—but it has lately been noticed that increased smoothness can in some cases actually cause greater frictional resistance, and we are forced to the conclusion that the friction between perfectly true and clean dry surfaces is the result of mutual attraction of the molecules comprising each surface and this attraction may be great enough to cause actual welding or seizure. The object of lubrication in the " boundary " state is to diminish the attractions of the metals for each other and this can be done by more or less " saturating " the free energy of the surfaces by placing upon them a liquid which is powerfully attracted to the surfaces.

When certain of these liquids are allowed to spread over a clean metallic face they immediately form an infinitesimally thin film of great stability which reduces the friction between the solids. These films may be even less than one hundred thousandth of an inch in thickness and they are held so strongly to the metal that they become rigid, having lost their mobility as fluids, yet two such films, one on each solid, slide over each other easily and protect the metals from contact and wear.

" Oiliness " may be defined as that property of a liquid which enables it to form powerful lubricating films when spread as an impalpable layer between two solids—it is not a property of oil " per se " any more than wetness can be said to be a " property " of water—it is a phenomenon strictly confined to the solid-liquid interface. A cup of water is not " wet " nor is a bottle of oil " oily " but if a solid be dropped into these liquids it may become wet or oily.

From the foregoing it will be seen that there are two distinct states of lubrication, namely, " fluid film " and " boundary " and it is also possible to have intermediate states which may be described as " semi-fluid. " The mechanical conditions which determine the type of lubrication are not only load and speed but also the " kind " of motion. Reciprocating movement of pistons is less able to produce a fluid film than rotational motion of main bearings, and the lubrication of gears presents yet further peculiarities.

The main bearings and big ends of motor engines operate under fluid film conditions while the rotational speed is fairly high—but it is obvious that just as they start from rest or are on the point of stopping, the film gets very thin and an element of boundary friction is present. The piston, gears, clutch and chassis components, springs, shackles, etc., rarely get perfect fluid lubrication and depend mainly on " semi-fluid " and " boundary " films.

Sir T. E. Stanton in a report to the Lubrication Research Committee of the Department of Scientific and Industrial Research expressed the opinion that " in general engineering practice the lubrication of all machine details in which the relative motion is of a reciprocating character may be taken as boundary lubrication and that consequently in such cases the improvements in efficiency due to the addition of fatty acid to the lubricants employed will be realised"—that is to say " GERM " oils treated on the Wells-Southcombe process.

SOME FURTHER DETAILS OF THE MECHANISM OF LUBRICATION

When a cylindrical journal is running at moderate load and speed, the lubricating oil is automatically dragged between the bearing and shaft owing to the motion, as already explained, and under ideal circumstances the shaft is floating on a layer of oil which effectually prevents metallic contact and the friction is simply due to the viscosity or resistance of the oil to shear. Under these conditions there should be no wear of the surfaces and the main characteristic of the oil is its viscosity.

The distance by which the shaft is separated from the bearing at the point of closest approach, i.e. the thickness of the oil film depends on the load, speed, and viscosity—such factors as clearance ratio, bearing length etc., need not be discussed at present; for any given viscosity, the higher the load the closer are the surfaces pushed together and, conversely, the higher the speed the more are they separated.

Very thin oil permits the surfaces to approach closely to each other and very thick oil tends to keep them further apart. On the other hand considerable heat is developed by churning action when a thick oil is employed and consequently the viscosity is reduced by the rise in temperature.

The frictional resistance in a bearing depends not only on the viscosity but also on the film thickness, a thick film giving a lower resistance than a thin one, but as we have seen, to secure a thick film it is necessary to use a relatively viscous mineral oil which sets up high resistance to motion by virtue of the internal friction of the liquid itself.

Consider, now, what happens if we supply a bearing with an oil too thick for its particular load and speed. The cold oil forms a thick film which on one aspect is favourable to the lubrication, but at the same time it results in a rise of temperature owing to the work done in churning the oil; this thins the oil, reducing the liquid friction, but also thinning the film and so increasing the friction. These opposing influences largely balance out and this is why a bearing will run quite well in a fluid state of lubrication with oils of fairly widely differing viscosity, but it is obvious that there will be a certain viscosity which will be ideal for the particular bearing—neither too thick nor too thin—and it is generally said that the best oil is the " thinnest that will do the work, " a rather vague statement.

There are numerous mathematical formulae connecting the load and bearing design with viscosity but unfortunately they are rarely applicable to machinery because there are certain variables the magnitude of which are unknown. For example a bearing may be designed to run at 200 lbs. per square inch at 500 R.P.M. at 30°C.—we could calculate what viscosity is required for this—but in practice these factors are never constant. The pressure may momentarily rise far over 200 lbs. and the speed may alter; the temperature will also vary between certain limits and these variations are not capable of numerical expression.

We therefore have to find the most suitable viscosity by experience and for safety's sake we invariably use a thicker oil than is strictly necessary.

Even then circumstances will arise which we did not bargain for—shock pressures, etc.—and it is to take care of these abnormalities that " oiliness " is demanded in the lubricant quite apart from viscosity.

The Lubricating Oil manufacturer nowadays produces oils of immensely wide viscosity range from the thinnest spindle oils to viscous dark steam cylinder oils. Many hundreds of oils differing only in viscosity are put on the market to meet the " whims " and " pet fancies " of oil users, and although this is a policy which is undoubtedly pushed to a ridiculous extreme there is nevertheless need for a very considerable range of viscosities, since two engines or machines by the same maker are never quite identical in their behaviour and requirements. The choice of viscosity for any given set of conditions, depends on many factors and in any individual engine these factors are varying from time to time, and even from moment to moment. At one instant the pressures are higher than at another, the speed may be continuously fluctuating and the temperature of the engine rising or falling. At the best, therefore, it is only possible to make a compromise from the ideal, and it is this which makes lubrication a good deal of an " art " as well as a science. There are of course several basic governing principles which decide the choice of viscosity for any particular purpose, chief of which are, the pressure to be supported, the speed of rubbing, the form of motion, the clearance in the bearing, the operating temperature and the system by which the oil is fed to the lubricated part.

The essential thing for which one strives is to ensure that a film of sufficient thickness is maintained between the bearing parts under the most severe conditions of operation, and when ordinary common mineral oils are used it is necessary to employ an oil of relatively high viscosity to take care of this condition, notwithstanding the fact that there will be some loss of efficiency due to the viscous drag consequent upon using an unnecessarily thick oil for the normal running conditions of the machine.

Quite apart from frictional considerations, the viscosity is often determined by operating temperatures. The temperature of a superheated steam cylinder is very high (up to 700°F.), hence we employ oils for this purpose which are very thick in the cold in order to ensure reasonable body at the working temperature.

The cylinder walls of Gas and Oil engines are much cooler than superheated Steam Cylinders, and so we can lubricate them with relatively thin oils.

For the Automobile there is a tendency among motorists to demand thicker oils than necessary owing to the mistaken notion that " treacly " oils maintain more body when hot. The use of exceptionally viscous oil is probably more responsible for piston wear in motors than is generally assumed owing to the inability of the cold oil to splash up to the cylinder when starting. It must be remembered, however, that in the petrol and oil engine the fuel generally contaminates the lubricant to some extent and consequently a thicker oil than necessary has to be used, to counteract this " thinning " action of the fuel. (*See Section on "Contamination of the Lubricant by Fuel," page* 56.)

When deciding on the most suitable viscosity for any particular purposes it must also be borne in mind that we have to consider not only the behaviour of the oil at the bearing surface but the method of getting the oil to the required place. Sometimes the lubricant must traverse a length of feed pipe in an exposed place and if the oil does not flow readily it may not arrive in sufficient quantity to keep the bearing supplied and many cases of engine failure are attributable to this cause.

The ideal lubricant would be one whose viscosity did not change with temperature so that there would be a free flow of oil in the cold while maintaining the full " body " when hot. In the chapter on viscosity attention has been drawn to the great difference between oils in this respect and a good viscosity—temperature curve is one of the most important criteria of an oil.

HOW THE "GERM" ACTS

The first essential of a lubricant is that it shall spread over the bearing surfaces and form a complete and permanent film which is not dislodged by pressure or motion. This film can only be formed by liquids which possess a certain attraction for solid surfaces, because, if the liquid is not attracted at all by the solid, it will just "run off," or, in more correct language, the liquid will refuse to "wet" the solid. For example, a candle dipped in water comes out dry, but if immersed in oil, it will come out covered with oil, i.e. "wetted" with oil. The reason is that water has no attraction for the wax of the candle, but oil has. Again, everyone is familiar with the fact that a bright steel surface, say, a knife blade, is not easily "wetted" by water, and the steel has only to be shaken well in the air for the water to completely leave it in small drops, while, on the other hand, it is very easily "wetted" by oil. Although all oils have some attraction for metals and consequently "wet" them, there is a difference in the degree or strength by which various oils are attracted and held to the metal, and "GERM" oils fix themselves more strongly than any other kind of lubricating material, owing to the fact that the "GERM," which is distributed throughout the mass of the oil, anchors itself on the metallic surface. This is no imaginery hypothesis, but is actually a reality which can be measured in several ways.

One method is to place a few drops of oil between two metal plates squeezed together by a heavy load and find the pull required to just cause the top plate to move over the fixed bottom plate. This is called the Static Friction and it is found that it is much lower for a "GERM" oil than for the best mineral oils.

Another method by which the film-forming properties of an oil can be measured is known as the Contact Angle method. This consists of placing a drop of the oil on to a metal plate and measuring the angle between the edge of the drop and the plate by optical means. "GERM" oils give a very low angle and it is known that the lower the angle the better the "wetting."

It has been pointed out in the preface that this remarkable effect is produced by treating mineral oils with a trace of certain higher fatty acids (less than one half of one per cent).

The uninitiated may express surprise that so minute an amount of fatty acid can so alter the properties of an oil and two simple illustrations may be given which although not strictly parallel yet depend upon similar physical facts, for example: it is difficult to wash anything with pure water but if less than one half of one per cent of soap is dissolved in the water, washing becomes an easy matter.

Again, the glass screen of a motor car on a rainy day becomes covered with little drops of water which do not run together, so that one has "wet" patches of glass interlaced with dry glass, but if the glass is touched with a trace of certain substances, such, as for example, soap, the drops of water run together forming a continuous watery film which "wets" the glass perfectly. This is analogous to the behaviour of "GERM" oils which form continuous persistent films on bearing surfaces owing to their great wetting power and strong adhesion.

In the preceding pages it has been explained how a fluid film of oil is formed between two surfaces in relative motion and it must be carefully borne in mind that this fluid film is due entirely to the MOTION of the metallic parts. All other things being equal, in the case of a cylindrical journal, the higher the speed the thicker is the oil film which is built up until a limiting value is reached or to put it the other way round, the slower the speed the thinner the film, and when motion actually stops there is no "dynamic" layer of oil between the surfaces and the shaft lies in more or less line contact with the brass. The expression "dynamic" film has been used to describe this particular type of lubrication produced by motion and in this state the metallic surfaces are completely separated by an oil layer of appreciable thickness. Hence we speak of this condition as Perfect Fluid Lubrication or Fluid Film Lubrication.

When relative motion becomes very slow or actually stops, or when the load is too high for the speed, fluid film lubrication breaks down and we have then to depend on another type of lubrication to protect the surfaces from seizure. This has been called "Boundary" lubrication because it deals with the boundary between perfect films and dry friction. It is in the Boundary State that "oiliness" is essential.

Not only the "rate" of rubbing influences the lubrication, but also the "kind" of motion.

In engineering we find several "kinds" of motion—in particular:

(1) Rotation as in plain bearings.
(2) Sliding as in pistons, valves, etc.
(3) Rocking as in pins, shackles.
(4) Reciprocating.

In the first of these types it is comparatively easy to maintain a fluid film, but in the other three cases it is much more difficult. A piston for example slows down and then stops at the end of each stroke and then reverses direction.

These are conditions which are very unfavourable to the maintenance of a fluid film and we must depend very largely on the "oiliness" of the lubricant to prevent metallic contact.

Again certain motion gear such as rocking pins cannot always be fed with a constant stream of oil and are liable to run with a deficiency of supply so that it is very desirable to employ an oil which "adheres" powerfully to the bearing.

All mechanism must sometimes stop and start and when the motion has fallen too low to maintain a "fluid" film or before the film is formed on restarting some wear will occur unless an "oily" lubricant is present. There can be no doubt that the main cause of wear and tear of engines and machines is to be found in these conditions where boundary lubrication occurs, and it is here that the "Germ" oil shows its greatest value simply because it preserves a lubricating efficiency greater than any other type of oil under circumstances which thin the film to vanishing point.

This is not simply the result of "slow motion" but is a function of speed, load, viscosity and rubbing conditions. Under circumstances which do not permit of fluid film lubrication J. H. Wells has been able to show that Boundary lubrication is a very definite and stable state at speeds as high as 150 ft. per minute at which speed the "Germ" oil continued to show about 20% greater lubricating efficiency than mineral oil of similar viscosity. The efficiency is also well maintained at elevated temperatures.

With a given load and speed the friction of a bearing falls as the temperature rises owing to the reduced viscosity of the oil causing less frictional drag until a "critical point" is reached where the oil has become too thin to completely separate the surfaces. Beyond this critical point the friction rapidly rises ultimately resulting in dry friction and even seizure.

The increased oiliness of "Germ" oils delays this critical point and in this way may save a bearing from seizure in the event

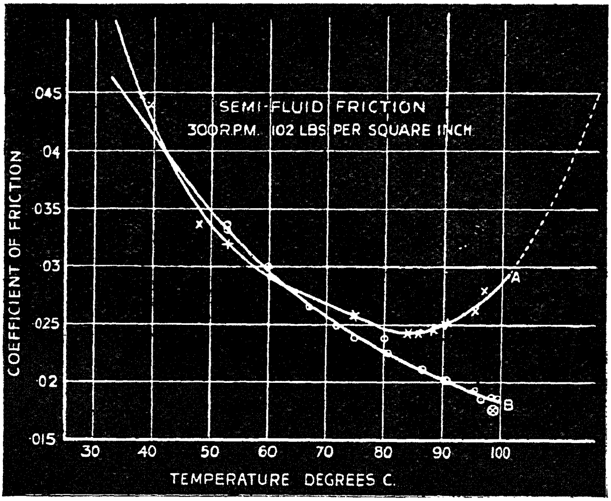


Fig 9.

of a temporary abnormality causing an excessive rise in temperature for a short period.

In Fig. 9, A is a good quality mineral oil showing a critical point at 85°C. B is a "GERM" oil of similar viscosity and the critical point has not been reached at 100°C. (212°F.)

PISTON LUBRICATION

The greatest mechanical loss due to friction in an engine occurs in the cylinders and a reduction of piston friction not only results in economy of power, but indicates that the metals are being protected from wear.

The formation of a "dynamic" type of film between cylinder and reciprocating piston is not so easy because there is no rotary motion to draw the oil between the rubbing surfaces and some experiments carried out at the National Physical Laboratory indicated that at very slow speeds the fluid film is absent and the lubrication is essentially of the Boundary or "Greasy" type.

At high piston speeds this cannot be quite true, a certain amount of fluid lubrication occurring but there is no doubt that a considerable element of Boundary friction is present and we prefer to speak of piston lubrication as semi-fluid. The remarkable life of pistons, often many millions of strokes, can only be accounted for by assuming that the annular spaces between the rings act as oil reservoirs in much the same way as grooves in a plain bearing.

There is nevertheless definite evidence that the friction of pistons is dependent partly on the chemical nature of the oil quite apart from viscosity and the "GERM" was found to give lower friction than mineral oils in the experiments quoted above (see Sir T. E. Stanton on "The Friction of Pistons").

This has also been confirmed on a large experimental Diesel where the mechanical efficiency was improved by replacing the mineral Cylinder oil with a "GERM" oil.

In Steam Cylinders the oil film is influenced sometimes by water and this will be discussed in a later chapter.

The temperature of the piston in internal combustion engines (Automobiles, Diesels, Gas Engines), has been measured in a few cases. It is of course dependent on the load, design and cooling efficiency but in ordinary circumstances it is about 450°F. (232°C.) in the neighbourhood of the top ring and rapidly falls away to about 250-300°F. (135°C.) at the skirt.

A good quality lubricating oil is fairly stable at these temperatures and does not oxidise or carbonise unduly but if too much oil is fed to the cylinders, especially in old and worn engines, a certain amount of creeping past the piston results and this excess oil is then exposed to flame temperatures in the combustion space and is destroyed, giving rise to carbonaceous residue whatever oil is used.

The permanence of the "GERM" film permits of the minimum oil feed to the cylinder and so reduces the tendency to form carbon while securing economy in lubricant consumption.

In automobiles the lubrication of the pistons is by far the most important consideration. Notwithstanding the great improvement effected during the last year or two by the metallurgical study of cylinder and piston materials as a result of which the " life " of these parts has been much increased—there still remains room for improvement in the reduction of cylinder and piston " wear." Unlike plain cylindrical bearings which are easily flooded with oil there is a difficulty in forming and maintaining a perfect fluid film between the piston and its cylinder, owing to the sliding and reciprocating form of the motion. The problem is complicated further by the great variation in piston temperature from cold to very hot, and by the fact that a large excess of oil is undesirable on account of the carbonisation troubles. Let us consider these points in greater detail especially with reference to vertical petrol and oil engines.

When an engine is stopped the oil on the cylinder walls begins to drain away and if a mineral oil deficient in " oiliness " or adhesiveness is employed the surfaces will retain so little after a prolonged rest that on restarting the lubrication is very imperfect until a sufficient number of strokes have been made to replenish the oil supply. This means that the piston is rubbing against its cylinder wall for a certain time with an insufficiency of lubricant which must result in a certain amount of wear.

By employing an oily lubricant, such as " GERM " oil, this objectionable effect is largely minimised, firstly because the oil anchors itself to the metal and does not completely drain away, and secondly because thin films of " GERM " oil possess about 25% greater lubricating efficiency than mineral oils.

When running on load the average temperature of the cylinder wall is somewhere around 250°F. and an oil should have viscosity in the neighbourhood of 50 seconds Redwood at least at this operating temperature. Unfortunately to obtain this viscosity at the piston temperature an oil will have a viscosity at 60°F. of over 3,000 seconds if it is good quality and inferior types may go to 4,000 or 5,000 seconds.

This means that the cold engine for a few minutes after starting has to use an oil from 60 to 80 times as thick as it requires when warm. Now as the majority of pistons depend for their oil supply on "splash" there will be a definite deficiency of lubricant on the cylinder at the start because thick oil does not splash so readily as thin oil. This is probably offset partly by the greater clearance of the cold piston and the greater lubricating efficiency of the thicker oil but the net result is distinctly unfavourable to lubrication.

An experiment made by the American Society of Automotive Engineers is interesting in this connection.

A Pierce Arrow truck engine was mounted on the bench and coupled to an electric motor—the current consumption of which could be accurately measured. The engine was cooled to definite low temperatures by circulating water and freezing mixtures through the cylinder jackets and the power required to turn the engine over at low speeds was measured.

It was found that the power required was proportional to the viscosity of the oil when the engine was " motored " electrically at speeds of a few hundreds revs. per minute. It was then decided to measure the " break away " torque, i.e. the force required to just move the crank from rest with various oils at low temperature. It was found that this force was almost independent of viscosity but was 25% lower with an oil of the " GERM " type than with an ordinary mineral oil—thus showing that the former had maintained a lubricating film of minimum friction.

The great variation in cylinder temperatures from cold to hot demands an oil of flat viscosity-temperature curve for successful lubrication, but the future will no doubt see developments in oil coolers which will narrow this temperature range and enable a less viscous oil to be used so that cylinder wear on starting due to " stodginess " will be minimised.

There is a further serious cause of cylinder wear resulting from lubrication, namely carbonisation of the oil due to oxidation and thermal decomposition.

There is a definite clearance between piston and cylinder or between shaft and bearing and this clearance should be filled with clear oil. Very soon after fresh pure oil has been used in an engine, traces of carbonaceous matter appear and if these particles are extremely minute in diameter and relatively soft in structure they are no objection to the lubrication because they are not big enough to bridge the clearance gap, but when they are large and hard they break through the oil film and act as abrasives.

In the chapter on oil testing it was pointed out that some oils oxidise readily and such oxidised matter is readily decomposed in the flame zone forming lumps of carbon. It is not simply the influence of temperature which has to be considered but also the stability of the oil towards oxygen which is always in great excess in cylinder and crank case. Similar abrasive action results from mineral dust sucked into the engine from the surrounding atmosphere, and there is still room for great development in air filters and oil filters to assist in the reduction of cylinder and piston wear from these causes.

In petrol engines dilution of the lubricating oil by petrol is another fruitful source of cylinder wear.

An astounding case of this recently came to the author's notice in which new cylinder blocks had to be fitted to a 'bus engine 600 miles after leaving the maker. In this case for some abnormal reason the lubricating oil was found to contain nearly

50% of petrol and the viscosity had been reduced to nearly that of the spirit.

THE DUAL PURPOSE OIL

It is now fairly general to employ one and the same oil for the lubrication of cylinders and bearings in moderate size internal combustion engines. Of course for certain enclosed types it is not practical to keep the cylinder oil separate from the bearing oil. In the petrol and crude oil engine the bearing pressure and speeds are so designed that one oil of viscosity suitable for the cylinders will suffice for the complete engine, but some engineers consider it an economy to use a high class oil for cylinder lubrication and a cheaper material for the bearings where these are of the open type.

UPPER END LUBRICATION

Some motorists are of opinion that the top end of the cylinders do not get sufficient oil splashed up from the cranks and a number of so-called upper cylinder lubricants have been placed on the market. These generally consist of a mixture of light machine oil with kerosene or burning oil and are mixed with the petrol in the fuel tank. The idea is that when the petrol is fired in the cylinder this machine oil is not burnt but deposits as an oily fog on the cylinder wall and valve stems.

In a well-designed engine this method of lubricating the top of the cylinder is unnecessary but there are cases where some advantage is found. It must always be remembered that excess oil in the combustion space will partially carbonise and the motorist who adopts this system must be prepared to decarbonise a little more frequently.

A good upper cylinder lubricant can be made by mixing one part of petrol with one part of light " GERM" motor oil and adding this mixture to the fuel in the proportion of about 2 ozs. per gallon.

EXTRANEOUS FACTORS INFLUENCING THE BEHAVIOUR OF LUBRICANTS

In the practice of lubrication many extraneous factors arise which may profoundly modify the properties of the oil and influence its lubricating efficiency. Such factors are :—

(1) Contamination of the lubricant by moisture, water, condensed steam (emulsification).

(2) Contamination by fuel, oxidation and polymerisation and carbonisation.

It will be desirable to briefly consider the cause and effect of such influences from the standpoint of the laboratory and of practice.

THE INFLUENCE OF WATER—EMULSIONS

Emulsions consist of minute globules of oil in water or of water suspended in oil. The former type are called oil/water emulsions and the latter water/oil. Milk is a naturally occurring illustration of oil/water emulsion while butter consists largely of the water/oil type. An immense amount of study has been devoted to Emulsification by Physicists and Chemists. It is very difficult to form emulsions of pure oil and pure water alone, the presence of a small quantity of some third substance called " the emulsifier " being necessary to produce complete and stable emulsions. The emulsifier appears to act by forming a very minute pellicle or coating around the globules which prevents them coalescing. In very perfect emulsions, like milk, the size of the globule of oil is exceedingly small and under the microscope these globules are seen to be in violent agitation, a state to which the term " Brownian Movement " is given in honour of its discoverer. The stability of an emulsion can be gauged to some extent by observations of the drop size and Brownian activity under the microscope. The size of the drops determines many of the peculiar properties of emulsions such as their colour, viscosity and stability.

Certain emulsifiers determine the type of emulsion which is produced when oil and water is violently agitated together and it has been noticed that soaps which are soluble in water cause emulsions of oil in water, while soaps of the heavy metals—iron, copper, zinc, etc., give rise to the reverse type in which drops of water are suspended in oil.

Finely divided solids can also act as emulsifiers and we often find slimes in engine crank cases in which minute particles of metal constitute one of the causes of emulsification. The ratio of oil to water may vary widely and as this changes, the appearance and viscosity undergo marked alterations and in some cases the emulsion becomes so thick that it behaves like a jelly or plastic solid. At a certain ratio of oil to water it is not uncommon to find a reversal of the emulsoid type, a water/oil formation changing into oil/water.

Mixtures of oil and water in an emulsified form frequently occur in engineering practice where they may be detrimental to the lubrication. It is impossible to avoid contamination by water or moisture in the lubricating system of many engines and machines and this condition demands careful consideration in the choice of a lubricating oil. It may be generally stated that wherever it is possible to lubricate by " dry " oil every effort should be made to secure this because the lubricating efficiency is at its maximum in the absence of water. Accordingly, in systems where the oil is circulated through bearings and allowed to rest for short periods in tanks, such as Turbines, it is desirable to employ an oil which readily separates from water, and so permits the Engineer to draw off the watery underlayer from time to time.

Methods of examining an oil for the property of demulsifying are described in the section on Tests but these must always be correlated with the oxidation or sludge value.

Small traces of water accelerate the oxidation of oil, and only a highly stable product should be used in turbines or forced feed steam engine crank cases.

In recent years such progress has been made by the refiner in the preparation of non-emulsifying oils that it is not uncommon to be able to run a turbine for very many months without changing the oil, but it should be noted that in general the thicker the oil the less stable it is and the success of turbine operation depends partly on the highly efficient oil-cooling system which enables relatively thin oils to be used and keeps the oxidising action of air to a minimum. Every effort should be made in such a circulating system to avoid aeration of the oil.

There are some cases where the oil is contaminated by moisture where it is not possible to effect a separation of the water, e.g. a wet steam cylinder and also for some purposes water is deliberately added to the oil to assist in cooling (Marine engine slides, cutting emulsions, etc.).

Wherever it happens that owing to special circumstances the oil must actually lubricate in the presence of moisture without any chance of separation, an oil which will partially mix with the water is to be desired. If a surface is thoroughly " wetted " by water, a pure hydrocarbon mineral oil will not readily spread over it, and conversely it is found that globules of water resting on a thin film of mineral oil spread over an iron plate, soon dislodge the oil, and small patches of rust become visible on the iron.

If a lubricant which is partially miscible with water or which is strongly adsorbed by metals (e.g. " GERM " oil) be substituted for the pure mineral oil, the surface is somewhat protected. To put this briefly—it is better to lubricate with a mixture of oil and water than just with water alone and if the mixture is such that the metal is coated by oil and the water droplets are dispersed in the bulk of the oil away from the metallic surface the lubrication will be quite efficient.

The principal cases in which this type of lubrication occurs are :—

(1) Cylinders using saturated steam, especially on starting.
(2) Cylinders subject to " priming " boilers.
(3) Marine type slides, etc.
(4) Hydraulic machinery.
(5) Air compressor cylinders (condensed atmospheric moisture).

Internal combustion engines may also occasionally be troubled by " wet " cylinders after a prolonged period of rest or due to actual leakage of water from cylinder jacket or water-cooled piston.

CONTAMINATION OF THE LUBRICANT BY FUEL

This occurs chiefly in the case of petrol and kerosene engines but occasionally with heavy oil engines. Gasolene dilution is due to a variety of causes chiefly the use of the air strangler in starting, faulty carburation and ignition and the occurrence of heavy ends in the fuel. The extent of the dilution varies greatly, not only with different engines but even with the same car depending upon the conditions of running, the atmospheric temperature, and the quality of the fuel. It is worse in winter than in summer and the engine which runs cool or frequently stops and starts will suffer more than the hot or long distance tourer.

The objectionable effect of dilution is simply that it may reduce the viscosity to a dangerous limit and this limit appears to be narrower with a mineral oil than with a " GERM " oil because the latter still preserves better lubricating properties when diluted. The reduction of viscosity by a given amount of petrol is relatively similar for all types of oil and the curve in Fig. 10 shows the average effect on a heavy and a medium motor oil.

It is seen that the viscosity of the oil is reduced to approximately one half by 6% of Gasolene (Petrol).

It is not possible to correlate the amount of dilution with the mileage on account of the above mentioned variations but experiments conducted in U.S.A. on a large number of vehicles indicate a characteristic curve shown in Fig. 11.

The point X on this curve differs according to circumstances but it is important to note that at a certain dilution an equilibrium seems to occur at which further quantities of petrol coming down are balanced by the amount which is being lost by evaporation from the crank case and in U.S.A. it has been proposed to deliberately add petrol to the fresh oil to arrive at this equilibrium point at the desired viscosity. Such oils have been called Equilibrium or Non-Absorbent oils.

If the rate of dilution were reasonably constant for all engines this method might be excusable, but no oil manufacturer would dare to do it in his Standard Grades for the lubrication of *all* kinds of engines.

The remedy for excessive dilution is obvious—eliminate the cause as far as possible, and if this does not result in a complete cure it will be necessary to use an extra heavy grade of oil and refresh the sump at fairly frequent intervals.

In Kerosene engines it is doubtful whether an equilibrium point can be recognised in practice owing to the non volatile nature of the diluent.

Automobiles in general are supplied with thicker oils than are strictly necessary or desirable from the lubrication standpoint chiefly because of this risk of dilution by fuel.

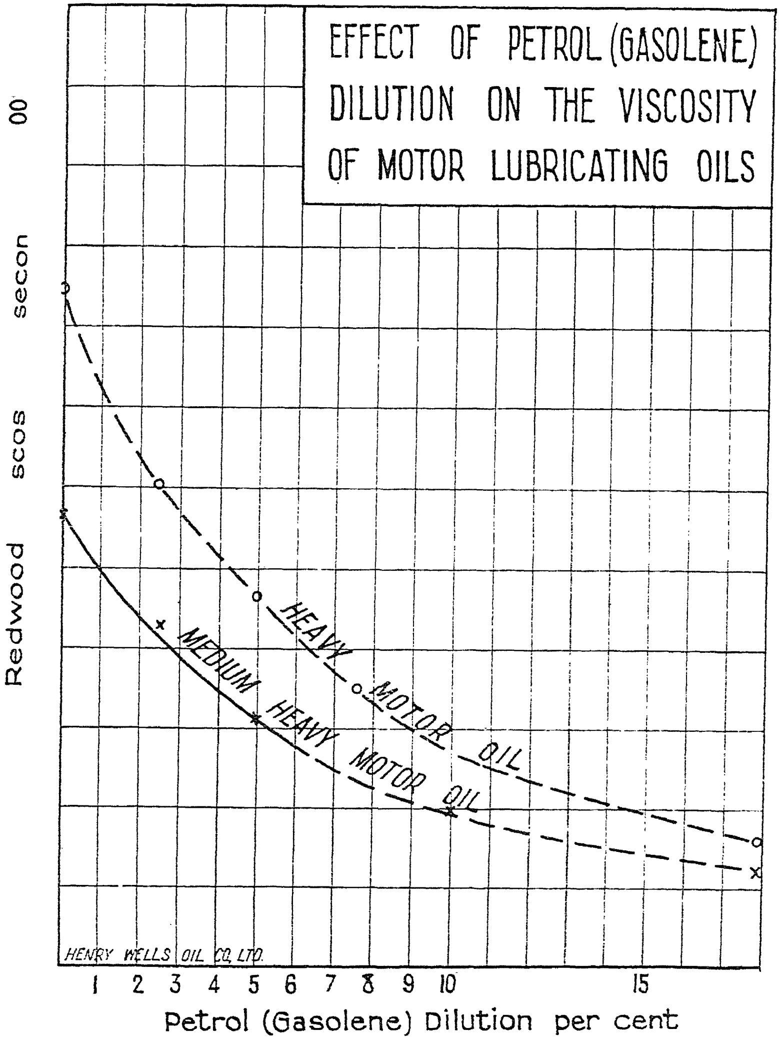
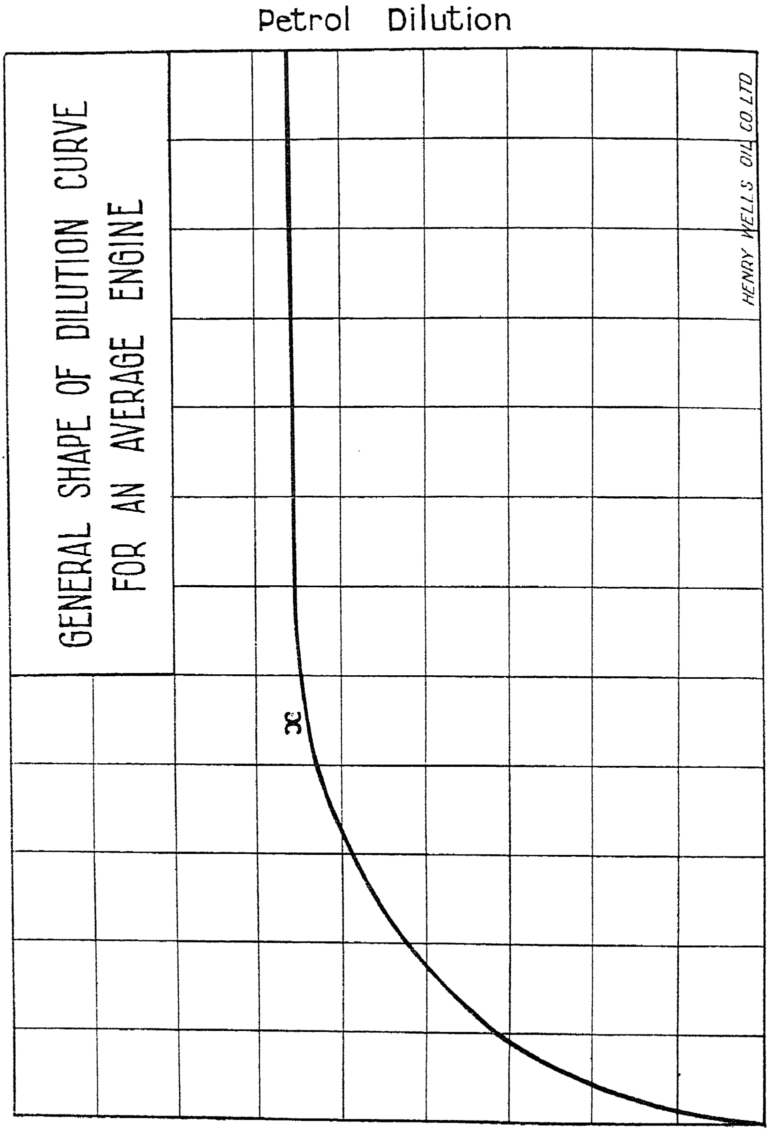


FIG. 10.



Petrol Dilution

FIG. 11.

OXIDATION, POLYMERISATION AND THERMAL DECOMPOSITION

It is interesting to trace the changes which lubricating oils undergo during prolonged use in the circulating systems of engines.

The combined action of heat and churning with air, results immediately in a certain amount of oxidation of the hydrocarbons of the oil, evidenced by the fact that the colour darkens very quickly. In a short time, varying with the nature of oil, the viscosity begins to increase but no definite separation of carbonaceous matter occurs and the lubricant keeps clear and bright, despite the change in colour.

There is no doubt that during this stage the oil is actually improving in lubricating efficiency. Measurements of the viscosity temperature coefficient indicate this and there is plenty of evidence from engine users that the lubrication is decidedly good. Experiments with a Buick engine, published in U.S.A. showed an increase in the power output after the oil had been in use for a short period.

As time goes on if there is no fuel dilution this thickening gets more and more pronounced until a point arrives when insoluble matter is formed and precipitates in the oil in the form of fine particles. These changes can readily be followed by periodic examination of samples under the microscope using a magnification of about 100 diameters. While these particles remain intensely minute, yet definite, all is still happy and well.

A later stage sees these carbonaceous particles growing in quantity and commencing to coalesce and finally separating from the bulk of the oil in the form of insoluble sludge.

We are now in the danger zone, and the lubricating system needs attention either by considerable refreshment with new oil or more economically by filtration. The trouble lies not so much in the impairment of the oil as a lubricant as in the risk of clogging of pipes, ducts, oil holes and grooves by the sludgy deposit which has a tendency to lodge in places where the stream is reduced in velocity.

There is a wide demarcation between the behaviour of different oils, not only in the length of time with which they resist this final objectionable stage, but also in the nature of the sludge, which is of vital importance to the safety of the engine.

It used to be considered that the only test for these variables was an appeal to the engine, but while the results of experience are still the most valuable guide, it is true to say that scientific methods of studying oil by highly specialised apparatus which has recently been devised, assist very materially in guiding the manufacturer to produce highly stable lubricants. Such stable and resistant oils will always be relatively expensive to produce but the extra initial cost to the engine user is amply repaid by greater economy in consumption and cleaner lubrication. The higher cost of these oils is due to two causes—firstly the crudes which yield them are comparatively scarce and secondly that greater care has to be exercised in refining.

Recently there has been considerable attention given to this subject by refiners and the use of what is called the " contact " refining process has been highly developed. In this method the crude oil after distillation and washing is mixed with various amounts of " activated earth " heated for a certain time and finally filtered to remove the earth to which the impurities cling. By repeated treatment in this way, pale oils of great purity can be obtained from the most unpromising material and when the process is applied to suitable crudes an oil of magnificent stability is produced. It may be well to mention here that colour alone is no guide to quality in this respect.

Certain high gravity oils on the market are almost colourless or just lemon yellow, yet they rapidly thicken and deposit in an oxidising atmosphere.

The modern tendency of engineering design is continually in the direction of improved methods of lubricating the moving parts. The oilcan, the wick syphon and the drip feed lubricator are fast giving place to the pump circulation system. This is sound progress and is the proper way to economise oil consumption.

Further than this the modern machine is being designed to avoid oil losses and no longer does the bulk of the lubricant " go on the floor." Automobile engines can now be made which use only a bare trace of oil and the contents of the crank case are used over and over again for hundreds of miles. The latest development in this direction, and one which will rapidly become general, is the incorporation of a filter unit with the machine or prime mover. These improvements bring into greater prominence the need for lubricants possessed of great resistance to oxidation and ease of recovery or cleaning and the importance of this to the oil manufacturer and the user cannot be over-stressed. We are entering upon a new era in the application of oils in lubrication and the conditions call for special consideration.

Certain oils when churned up with hot air for a comparatively short period of time rapidly thicken, become black and deposit carbonaceous matter while a superior class remain quite bright and clean. After prolonged use all oils decompose somewhat but there is a great demarcation between the nature of the decomposition products. The oils of high specific gravity generally form a very fine slimy deposit which is filtered only with great difficulty while certain types on the other hand give a more granular precipitate which is readily removed and which leaves the filtered oil in excellent condition. It will be obvious that economy will result to the user from the employment of the latter type of oil, notwithstanding the fact that they are dearer in first cost and will probably tend in the future to increase in price as the law of supply and demand operates because such oils are not so prolific and are more costly to refine than the more common types.

There is still some controversy regarding the behaviour of different oils when exposed to the flame temperatures in an internal combustion engine and many bitter debates have been held between the supporters of the Paraffin base oils on the one hand and the Asphaltic on the other. The real truth is that no oil can stand exposure to a burning flame without decomposition and formation of solid carbonaceous material but the physical structure of the solid deposit obtained from these two great families of oil is markedly different. The carbon formed by the Paraffin oil hydrocarbons is harder than that from the Asphaltic.

These remarks particularly apply to that portion of oil—minute in amount—which actually gets into the combustion space " in the form of a fog." The film of oil which is adhering to the cylinder wall and exposed to the hot gases during the firing stroke does not suffer so violent a thermal decomposition as is usually supposed because it is kept comparatively cool by the metal wall whose temperature averages not many degrees above the boiling point of the jacket water.

This oil film is subjected to oxidation rather than thermal decomposition.* If the Conradson Carbon value is any *measure of the amount* of carbon deposit formed by any oil we should expect less from the Asphaltic type in the fresh unoxidised state but more from that portion which has already been exposed to oxidation.

It is the Author's opinion gathered from much experience that there is little to choose between these two types of hydrocarbon mixtures as to the amount of carbonaceous matter obtained from them by thermal decomposition in engines but it is certain that there is a difference in hardness. The naphthenoid oils of Russian origin occupy an intermediate position in this respect.

Each type has its advantages and disadvantages and a carefully chosen mixture of the two gives a " balanced " lubricant which is the ideal for general use. A word may be introduced here about the so called super refined oils of asphaltic origin recently placed on the market. These products of extremely low Conradson value are found to oxidise comparatively easily and the oxidised oil gives much higher carbon residues. It would appear that the super refined oils tend slowly to revert in use to the characteristics of the original crude and this is an experimental fact for certain of the lighter oils such as are employed for Transformers and

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* By thermal decomposition is meant destruction of the hydrocarbon molecule by "cracking" but it is realised that the process is also accompanied by oxidation.

The following table shows the difference between two oils intended for Diesel engine lubrication and clearly indicates the futility of judging an oil on the Conradson value of the fresh oil. By the Conradson test oil B would be judged better than A but after oxidation the figures are reversed.

	Viscosity.		Coke Percentage.	
Oil.	Before Oxidation.	After Oxidation.	Before.	After.
A.	100	160	0.58	1.56
B.	100	280	0.40	2.10

THE RECLAIMING OF USED LUBRICATING OIL

ECONOMIES in the annual bill for Lubricating oil are effected much more satisfactorily by the careful recovery or re-use of the dirty oil than by the purchase of cheaper material. The expense of lubrication lies chiefly in the wastage of oil. One of the simplest ways of keeping down cost is to use the waste oil from an engine on some cruder plant and in Quarries and Collieries it is quite customary to lubricate runways, chains, etc., with the spent oil from the Power House. When the installation provides no opening for this kind of " secondhand " lubricant or when the Power Plant is oiled by a circulatory system, it is desirable to instal some sort of recovery plant. The choice of oil reclaiming system employed depends upon the quantity to be treated and the desired purity of the recovered oil.

For a few gallons per week it is obvious that a costly installation is uneconomical and there is also nothing to be gained by producing a " perfect filtrate " for re-use on some comparatively rough mechanism. On the other hand a Power House containing a number of Diesel units or steam turbines requires a good recovery process giving a clean product and necessitates the choice of an easily treated oil when originally filled and for daily " make up."

Depending upon the requirements, six methods of purification of dirty oil are available, namely :—

(1) Simple Settling or clarification.
(2) Settling assisted by simple gravity filtration.
(3) Purification by passage of oil through hot water, or of chemically treated hot water through oil.
(4) Clarification by removal of impurities by chemical means.
(5) Filtration by centrifugal machines.
(6) " Edge " filtration.

The above classification includes all the usual " practical " appliances on the market but there are possibilities for the use of earth " contact " processes, in which a real refinement of the oil takes place, for installations where the recovery runs into tons per week. Roughly speaking where the quantity of oil to be treated is less than fifty gallons per week, methods (1), (2), and (3) are applicable unless the special requirements call for an exceptionally clean oil.

The simplest method consists in allowing the dirty oil to stand in a tank, preferably warm, with taps at different levels to draw off the clarified material. The clarification is very slow and the losses are big, and it may happen with certain oils that they persistently refuse to become clear. Moreover, it is impossible to remove colloidal carbon in this way so that the oil remains black.

An improvement can be effected by settling the oil in the first place and then causing the settled product to traverse a filter pad, such a device is manufactured by A. C. Wells & Co., but again the process is slow although a better recovery is obtained.

The impurities to be removed from dirty oil may be broadly classified as :—

(1) Water.
(2) Metallic particles from engine wear and " grit " from the air and floor—in automobiles, road dust.
(3) Particles of carbon produced by the decomposition of the oil at high temperature.
(4) Fuel from I.C. engines—petrol, kerosene, heavy fuel oil.

The first three of these classes are suspended in the oil in particles of appreciable size and can therefore be removed by mechanical means except in the case of colloidal carbon, when chemical assistance is required. Fuel on the other hand is dissolved in the oil and can only be removed by a process of distillation. The plant required for waste oil recovery comprises a preliminary treatment tank, a filtering device and a cleaned oil storage vessel. The clarification can be accomplished either by a centrifugal machine, working on the cream separator principle, or by an edge filter. There are several makes of the former on the market differing in the detail of design and arranged to run at various speeds from 6,000 R.P.M. up to 15,000 R.P.M. The general principle of all such centrifuges is to magnify the force of gravity to produce a rapid settling out of the insoluble impurity. The centrifugal forces depending on the speed and diameter of the rotating bowl are claimed to be as great as 13,000 times that of gravity, in the device of Sharples, but the efficiency of cleaning is also dependent on the design of the separation chamber or bowl.

The " edge " filter embodies rather a novel principle. It is found that if a liquid containing particles is forced against a pile of thin sheets placed like a pack of cards, the solids are retained at the " edges " of the sheets and only the clear liquid passes between the sheets. In practice the filter medium consists of thin annular discs of either paper or metal built into the form of a tube and immersed in the oil under pressure.

Whatever method of filtration is chosen, the quality of the filtrate can generally be improved by a preliminary treatment, although this is by no means essential if the oil to be recovered is not particularly dirty and a high degree of purification not required.

The simplest treatment consists of subjecting the dirty oil to the action of boiling water in a tank for a few minutes and then allowing to settle before passing the supernatant oil through the centrifugal or filter. About equal volumes of water and oil are taken and it is useful to add to the water about 2% of some weak alkali such as Trisodium Phosphate, Sodium Silicate, or Soda Ash.* This causes the finer particles to coalesce and separate. In some cases great success has attended the use of special chemical treatment. For example, manganese resinate is dissolved in the hot oil, and a boiling aqueous solution of sodium silicate mixed with it. Insoluble manganese silicate is formed on which the colloidal carbon is deposited and so easily removed. The best treatment to adopt depends on the particular conditions but it is always advisable to see what happens by simple filtration or centrifuging before resorting to special methods since in most cases a sufficiently clean oil can be obtained by mechanical means. Petrol can be partially removed by heating the oil, preferably in a vacuum but there is no simple way of eliminating Kerosene or heavy fuel oil.

In conclusion it should be noted that the quality of the original lubricating oil largely influences the recovery process and in general a poor type of oil presents greater difficulties and losses in purification than a high grade well-refined product.

Provided the dirty oil has not been badly contaminated with fuel oil it is possible with these centrifugal machines or streamline filters to effect an excellent cleaning and recovery of " used " oil and such recovered oil is quite suitable for further use in engines ; in fact, except that it is somewhat darker in colour—a point of no importance—the lubricating properties are fully maintained. It is, of course, desirable to see that the viscosity of the filtered oil is not materially different from the original.

In reclaiming " Germ " oils *strong* alkalis should not be used.

SOME REMARKS ON SPECIFICATIONS FOR LUBRICATING OILS

SPECIFICATIONS fall into two classes :—

The object of the specification may be to indicate clearly what particular properties are desired in an article to render it suitable for some special purpose, but more usually a specification is made out simply to ensure constant deliveries of an oil which has already been found to give satisfaction in practice.

Can either of these objects be achieved ?

Unfortunately lubricating oil specifications are very rarely drafted by people with accurate knowledge and experience on both sides of the question. They are generally drawn up by engineers who clearly know what the engine wants, but they have insufficient knowledge of oil to be able to describe the requirements in the language of the oil technologist.

Specifications of the second type are often outlined by chemists who have no engineering experience and whose knowledge of the oil industry is strictly limited. On the other hand the commercial point of view must be considered in drafting specifications for it is undesirable to include figures which will make the article more costly to produce than is necessary for the purpose intended.

In no business has the amateur dabbler had greater scope than in lubricating oil and one often sees specifications which have obviously been drafted by people thoroughly ignorant of some of the most elementary properties of oil.

Many years ago comparatively little scientific research had been done on lubricating oils and rough and ready tests were done by engineers such for example as heating the sample for a few hours in an open dish, and judging the condition of the residue by rubbing it on the hand. We still see specifications which ask for volatility tests in open dishes although it is now well known that such tests are valueless unless the dish is of definite shape, exposed to an accurately measured current of air or steam at an absolutely constant temperature.

To return to the question—Can a specification be drafted to ensure that an oil will be perfectly satisfactory for a given purpose ?

There are many whose opinion is authoritative who would answer this question in the negative partly because they would remark that the complete requirements of an engine or machine are not accurately known and also because oil in the chemical sense is such a heterogeneous mixture that you can never be certain of constancy of the material.

Strictly speaking this is a correct scientific attitude of mind and perfection has certainly not been achieved, but in the average case there is no doubt that we have enough knowledge nowadays to choose the oil which will give satisfactory service even if we cannot say that it is the best possible for the job, but this can only be done by specifying a number of special tests and correcting the results of one with another.

To a lesser degree this applies also to specifications intended simply to ensure constant delivery of a well tried oil.

Suppose for example only one viscosity figure and a flash point is specified—hundreds of mixtures can be made to meet these figures. Now add a specific gravity and viscosities at 2 or 3 temperatures—perhaps only a dozen blends can be made to suit this.

Add further a cold test—a Conradson and an oxidation figure and the specification can only be met by oils of very closely similar composition.

It occurs occasionally that in specifications which give only a couple of viscosities, a gravity and a flash point, the figures are impossible of attainment showing that the author of the specifications is not properly informed on the subject. The following table gives a few figures for the world's best and the world's worst oils so far as these tests are concerned :

	Best.	Worst.	Best.	Worst.	Best.	Worst.
Sp. Gravity @ 60°F. ..	880	930	885	940	893	950
Closed Fl. Point ..	420°F.	under 370°F.	425°F.	under 370°F.	430°F.	under 370°F.
Redwood Viscosity :						
@ 70°F.	700	700	1,400	1,400	2,700	2,700
@ 100°F.	270	220	460	390	950	650
@ 140°F.	110	80	165	120	280	190
@ 200°F.	51	40	62	49	85	62

It frequently happens that very slight differences in a specification have a marked effect on the cost of production of an oil. For example an oil specified to give a Redwood viscosity of 2,000 seconds at 70°F. and not less than 68 at 200°F. may easily cost 2d. per gallon more to produce than one giving 66 at 200°F. while being similar at 70°F. This often gives an unfair advantage to an unscrupulous supplier who " risks " the odd couple of seconds.

BIBLIOGRAPHY

ON the subject of oil and lubrication there is an extensive and highly specialised literature and the following list gives only a few of the more important standard works on the subject.

To assist the Student these have been roughly grouped into three classes:

A. Chemical technology and analysis of oils.
B. Practice of Lubrication.
C. Mathematical and Theoretical.

For the most up to date study the various current scientific journals must be perused.

A. CHEMICAL TECHNOLOGY AND ANALYSIS OF OILS.

Archbutt & Deeley	*Lubrication and Lubricants* (C. Griffin).
Bell ..	*American Petroleum Refining* (Van Nostrand).
Day ..	*Handbook of Petroleum* (J. Wiley & Sons).
Evans ..	*Lubricating and Allied Oils* (Chapman & Hall).
Gurwitsch & Moore	*Scientific Principles of Petroleum Refining* (Chapman & Hall).
Holde	*Hydrocarbon Oils and Saponifiable Fats* (J. Wiley & Sons).
Hurst	*Lubricating Oils and Greases* (Scott Greenwood).
Kewley	*Petroleum and Allied Industries* (Baillière, Tindall & Cox).
Lewkowitsch	*Oils, Fats and Waxes* (Macmillan).
Nash & Bowen	*Principles and Practice of Lubrication* (Chapman & Hall).
Redwood, Sir B.	*Petroleum and its Products* (C. Griffin).
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B. THE PRACTICE OF LUBRICATION.

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Hyde	*Lubrication and Lubricants* (Sir I. Pitman & Sons).
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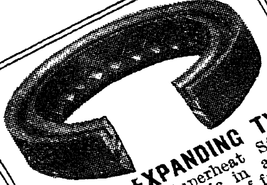

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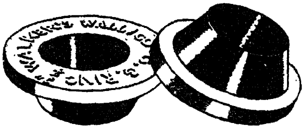

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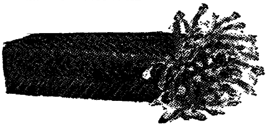

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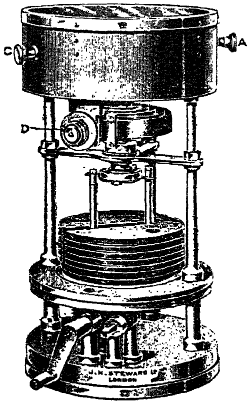

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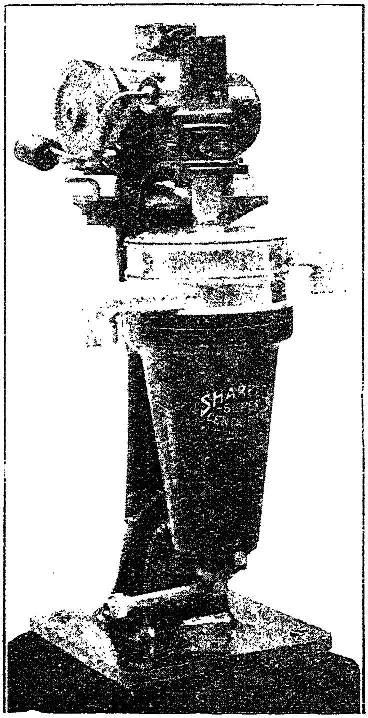

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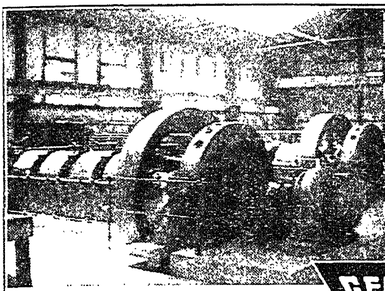
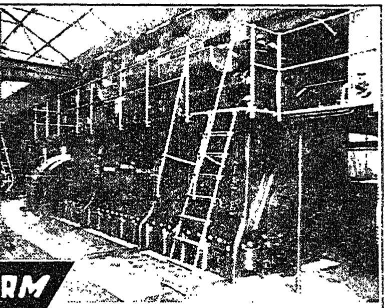


Two 300-H.P. Crossley-Premier Oil Engines.



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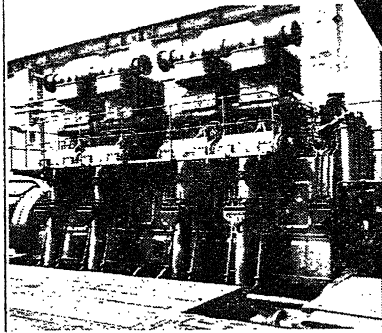
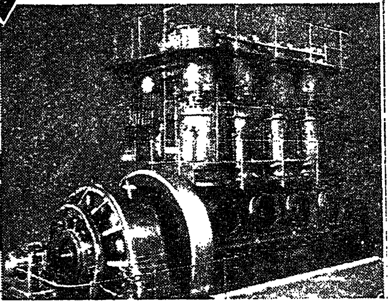


1440 B.H P. English Electric Fullager Engine.



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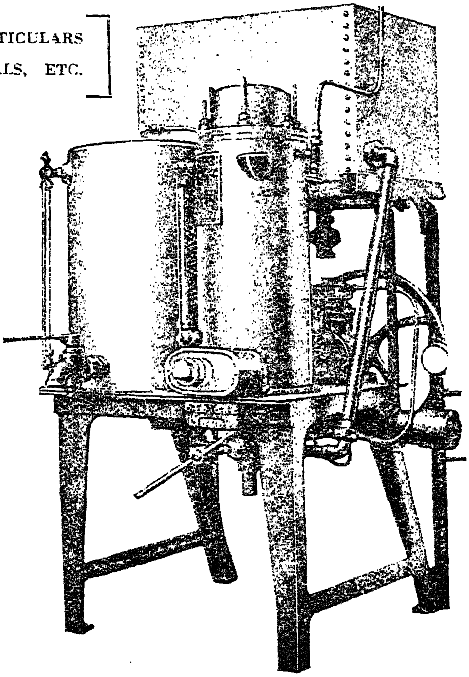

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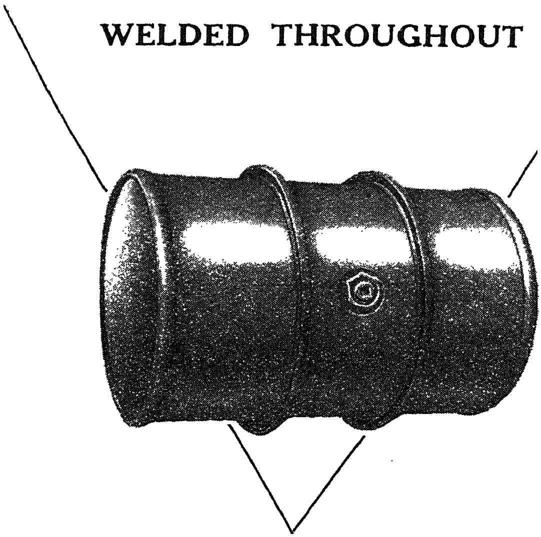

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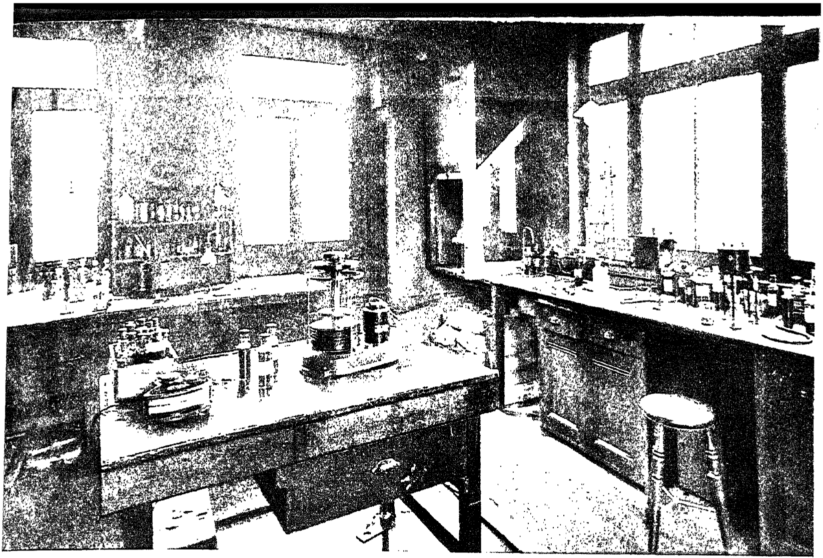

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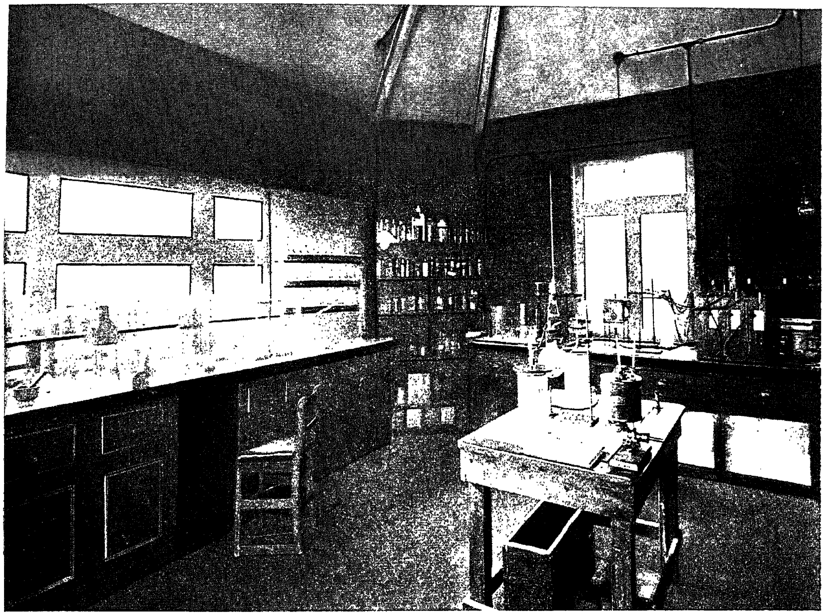

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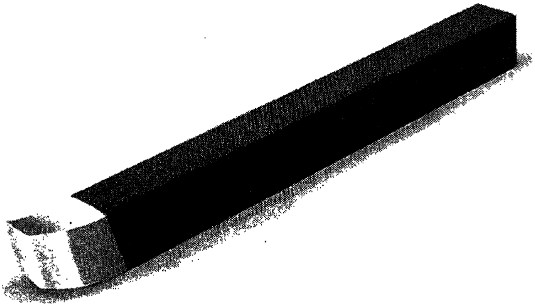

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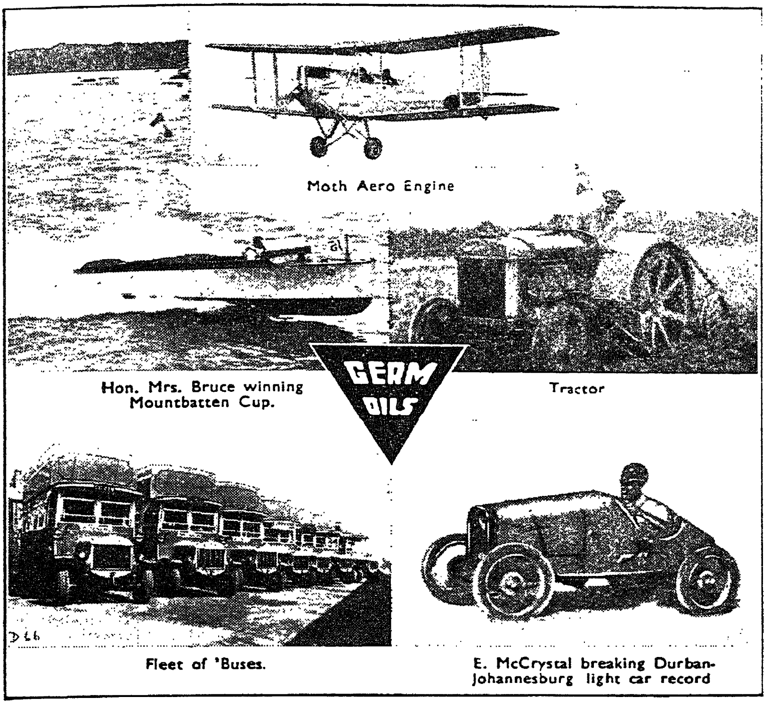

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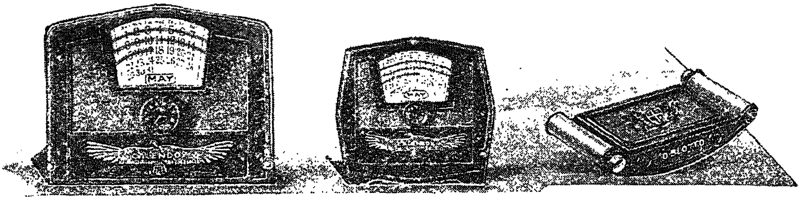

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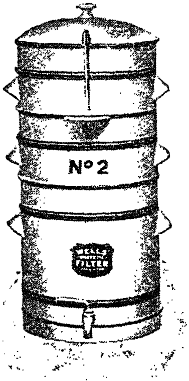

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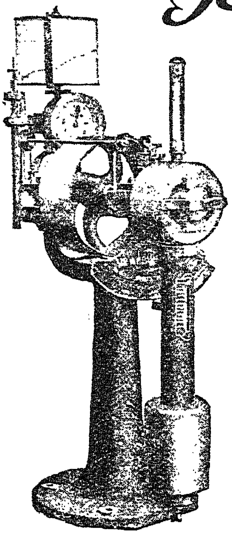

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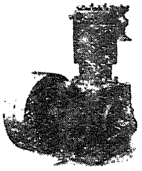

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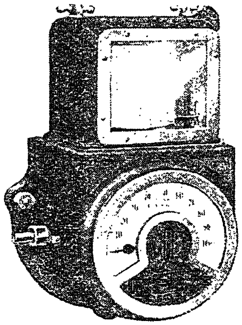

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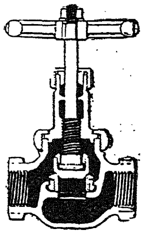

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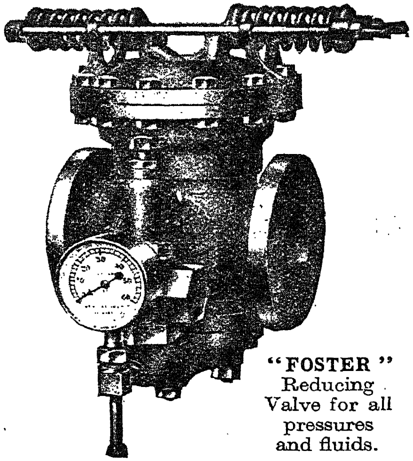

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